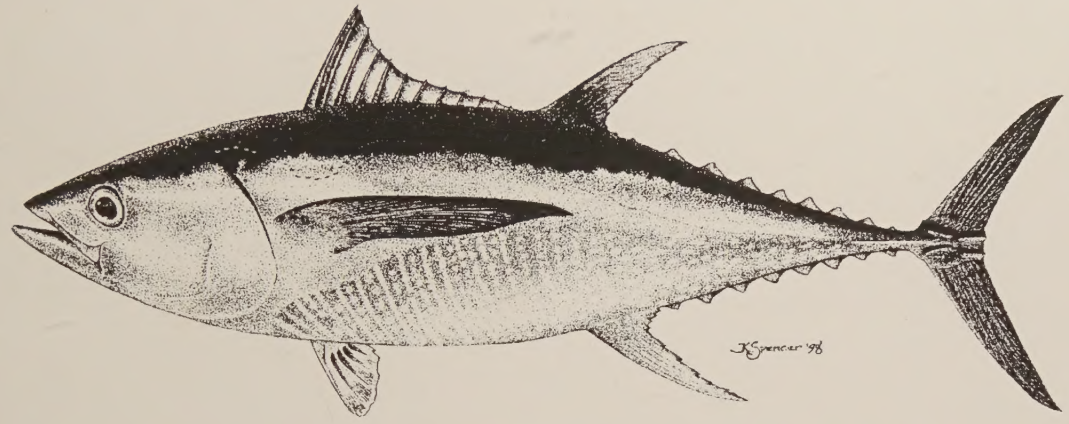
FAO Fisheries Circular No. 963 FIRM/C963
ISSN 0429-9329

RESEARCH IMPLICATIONS OF ADOPTING THE PRECAUTIONARY APPROACH TO MANAGEMENT OF TUNA FISHERIES



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PREPARATION OF THIS DOCUMENT

This Circular is the main outcome of the Expert Consultation on Implications of the Precautionary Approach for Tuna Biological and Technological Research held in Phuket, Thailand from 7 to 15 March 2000. The Consultation originated from a recommendation of the ICCAT[1] Tuna Symposium held in Ponta Delgata, Sao Miguel, Azores, Portugal in 1996. The Symposium recognized the existence of similar research problems with the implementation of the precautionary approach to tuna fisheries management on the global scale. Further information on the Consultation can be found in its Report presented here as Appendix 3.

FAO.
Research implications of adopting the precautionary approach to management of tuna fisheries.
FAO *Fisheries Circular*. No. 963. Rome, FAO. 2001. 74p.

ABSTRACT

This Circular presents the main outcome of the Expert Consultation on Implications of the Precautionary Approach for Tuna Biological and Technological Research held in Phuket, Thailand, from 7 to 15 March 2000. The administrative Report of the Consultation is also presented in the Circular as Appendix 3. The Consultation was organized in response to the adoption of the precautionary approach to fisheries management in: (a) the Agreement for the Implementation of the Provisions of the UN Convention on the Law of the Sea of 10 December 1982 Relating to the Conservation and Management of Straddling Fish Stocks and Highly Migratory Fish Stocks and (b) the Code of Conduct for Responsible Fisheries.

The Circular presents the implications of the precautionary approach for stock assessment, biological and environmental research and data collection. They apply to principal market tunas and most important billfishes. It addresses the need for the identification, quantification and reduction of major sources of uncertainties in the knowledge on species being targeted by fisheries, by-catch species and those ecologically-related and on their physical environment, particularly on the impact of fisheries on them. This quantification and reduction of uncertainties necessitates improvements to the existing methods and the developments of new methods. The reductions in the uncertainties may allow the adoption and implementation of safer and more optimal fishing regimes, potentially benefitting the industry and the community at large.

[1] International Commission for the Conservation of Atlantic Tunas.

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ACKNOWLEDGEMENTS

The preparation of this Circular was possible only due to a close collaboration of various institutions and individuals. The Expert Consultation on Implications of the Precautionary Approach for Tuna Biological and Technological Research (held in Phuket, Thailand from 7 to 15 March 2000) was co-organized and co-sponsored by:

- the Commission for the Conservation of Southern Bluefin Tuna (CCSBT),
- the Food and Agriculture Organization of the United Nations (FAO),
- the Indian Ocean Tuna Commission (IOTC),
- the Inter-American Tropical Tuna Commission (IATTC),
- the International Commission for the Conservation of Atlantic Tunas (ICCAT), and
- the Secretariat for the Pacific Community (SPC)

in collaboration with:

- the Department of Fisheries of the Royal Government of Thailand.

The Consultation's Steering Committee (SC) listed below contributed significantly to its organization.

- Dr Robin Allen (Consultation Chairman and Director of IATTC, La Jolla, USA),
- Mr David Ardill (Secretary of IOTC, Victoria, Seychelles),
- Dr John Hampton (Consultation Vice-Convenor and Principal Fisheries Scientist of SPC, Noumea, New Caledonia),
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- Mr Campbell McGregor (Secretary of CCSBT, Canberra, Australia),
- Dr Peter Miyake (Assistant Executive Secretary of ICCAT, Madrid, Spain) and
- Dr Ziro Suzuki (Consultation Vice-Chairman and Director of the Pelagic Fish Resources Division of the National Research Institute of Far Seas Fisheries, Shimizu, Japan).

Dr Hongskul and his staff ensured excellent arrangements in Phuket and provided support and assistance during the Consultation. The Department of Fisheries of the Royal Government of Thailand, especially the Andaman Sea Fisheries Development Center (AFDEC) and the Phuket Marine Biological Center (PMBC), assisted with securing these arrangements and provided hospitality for the Consultation. Generous hospitality was also provided by the Thai Oceanic Tuna Fishery Cooperatives, Ltd. (TOTFIC) and the Phuket Fishing Port of the Fish Marketing Organization (FMO).

The four Working Groups (WGs) created to carry out the preparatory work for the Consultation significantly contributed to drafting the paper presented in the Circular. Particularly, the effort of their Convenors (Drs Alain Fonteneau, Michael Hinton, Joseph Powers, and Joel Prado) and Vice-Convenors (Mr Alejandro Anganuzzi and Drs Lindsay Chapman, Richard Grainger, and Patrick Lehodey) needs to be acknowledged. All the experts participated in the preparatory work and in the Consultation at the cost to their employers. Dr Allen, Consultation Chairman efficiently led the Consultation to its successful outcome. Dr Willian Bayliff (IATTC, La Jolla, USA) edited the paper presented in the Circular. Ms Anne Van Lierde (FAO, Rome, Italy) formatted the Circular. FAO financed the publication and distribution of this Circular.

EXECUTIVE SUMMARY

This technical paper deals with the species of tunas and billfishes of greatest commercial importance. The tunas include skipjack, *Katsuwonus pelamis*, yellowfin, *Thunnus albacares*, bigeye, *T. obesus*, albacore, *T. alalunga*, Atlantic northern bluefin, *T. thynnus*, Pacific northern bluefin, *T. orientalis*, and southern bluefin, *T. maccoyii*. The billfishes include swordfish, *Xiphias gladius*, Atlantic blue marlin, *Makaira nigricans*, Indo-Pacific blue marlin, *M. mazara*, black marlin, *M. indica*, white marlin, *Tetrapturus albidus*, striped marlin, *T. audax*, Atlantic sailfish, *Istiophorus albicans*, and Indo-Pacific sailfish, *I. platypterus*. There are many other species of tuna, and several other species of billfish, of lesser economic importance. When general statements are made concerning tunas or billfishes they do not necessarily apply to species other than those listed above. They are often collectively referred to as "tunas and tuna-like fishes" in this report.

IMPLICATIONS FOR STOCK ASSESSMENT

The goal of any fishing management regime is to manipulate fishing mortality rates in order to achieve management objectives and to maintain the fishery within management constraints. The particular objectives and constraints chosen by managers imply that certain research and monitoring activities be addressed so that scientists may evaluate the effectiveness of the management and predict the likelihood of alternative future management outcomes. One component of these objectives and constraints is those associated with Precautionary Approaches to management, namely those associated with management targets and limits relating to overfishing rates and the status of an overfished condition. The scientific obligations to Precautionary Approaches is to determine the status of the stock(s) in question relative to limits and targets, to predict outcomes of management alternatives for reaching the targets and avoiding the limits, and to characterize the uncertainty in both of these. These impose some specific needs for research for stock assessments and monitoring.

A convenient framework to conduct management evaluations is through the use of control rules, for which managers specify variables under their control through some functions related to the status of the stock under a pre-agreed plan for adjusting management actions. Stock assessment research is then conducted to determine the status of the stock(s) in question, to evaluate the likely efficacy of management alternatives, to test the performance of management rules relative to precautionary targets and limits, and to characterize the uncertainty in the scientific advice for management. It is recognized that this involves continuous periodic feedback between managers and scientists with monitoring, re-evaluation, testing, and adjustment of management strategies.

Several suggestions for assessing the status of tunas and tuna-like fishes in relation to the Precautionary Approach are made. Most importantly, models should be developed and research conducted to determine the inputs to those models that appropriately characterize the uncertainty in the status determination. For example, research should lead to the use of estimation procedures with statistical error structures based on comparison among values predicted by the model and values observed in the fisheries. Changes in fishing strategies and their effects on estimation of indices of abundance should be considered, alternative scenarios to account for the problems in interpreting catch rates as indices of abundance should be incorporated into the evaluation of uncertainty; and empirical methods with appropriate evaluation should be employed in data-poor situations until more data are collected and research is conducted which allows the use of more detailed methods of stock assessment.

Quantification of the uncertainty associated with the estimates of the status of a stock relative to a specified reference point is complex, and there is a great need for research to improve and develop the mathematical techniques for doing this. The complexity arises because of the

variety of data sources, the numerous types of input required, and the limited knowledge about the underlying processes. Uncertainties that lead to estimation error in stock assessments result from observation error (through measurement and sampling) and model error (through the use of erroneous estimates of parameters and through model mis-specification errors). Several approaches may be taken to integrate uncertainty into the models, but, regardless of the approach used, the quantification of the overall uncertainty of an estimate conceptually involves a four-step process in which (1) a set of hypotheses is developed for each potential source of error; (2) a relative weight or probability is determined for each hypothesis; (3) the likelihood (degree of fit) of the resulting estimate is determined for all combination of the hypotheses; and (4) the results are integrated over probabilities and hypotheses.

In order to do this, there is a need for additional research on approaches for incorporating results from diagnostics such as residual and retrospective analyses into the evaluation of overall uncertainty. Also, it is important to attempt to harmonize and integrate different judgements into a single prior assumption of plausible hypotheses. A comprehensive approach to the quantification of uncertainty is likely to be computationally intensive. If such a process is to be adopted, it is essential that sufficient resources be allocated to the task.

IMPLICATIONS FOR BIOLOGICAL AND ENVIRONMENTAL RESEARCH

Tunas and billfishes have many biological and physiological characteristics that make them unique among marine fishes. Among these are streamlined body shapes and physiological adaptations to permit sustained high-speed swimming and efficient thermoregulation. The latter makes it possible for them to move quickly between surface and deeper waters. All of these characteristics facilitate their highly-migratory nature.

For most tunas there are insufficient measures of many important biological parameters, such as age and growth, stock structure, natural mortality as a function of age, mixing rates, and stock-recruitment relationships. Therefore, for the application of the Precautionary Approach to the tunas, it is important that the uncertainties regarding biological characteristics be identified and taken into account in stock assessment (and management). Substantial amounts of research are clearly required to reduce these uncertainties. Large-scale tagging programs appear to have promise for obtaining better estimates of many of these parameters, including movement patterns relatively to environmental conditions, natural mortality, growth, etc.

There is a growing acknowledgement worldwide that abiotic and biotic environmental changes significantly affect the distributions, and perhaps also the productivity, of various tunas. Thus it is important to determine the nature and extent of the impact of climate variability upon the pelagic ecosystems and the tuna stocks. This natural variability of the pelagic ecosystems should be taken into account as an additional source of uncertainty in stock assessment and management.

In most fisheries for tunas the by-catches tend to be relatively minor compared to those in fisheries for many other species, such as shrimp, but there are some tuna fisheries that take large by-catches. Furthermore, various marine populations, such as albatrosses, turtles, and some sharks, because of their life history characteristics, can be highly vulnerable to small amounts of fishing mortality. As little is known about the biology of many of the by-catch species, or the species compositions and magnitudes of the by-catches in many major tuna fisheries, it is impossible to assess the impact of the fisheries on by-catch populations. It is necessary, therefore, to conduct systematic observer programs to collect reliable information on by-catches. Appropriate indices of vulnerability should be developed across phyla to identify the most sensitive by-catch species discarded by the various tuna fisheries. Simultaneously, it should be accepted that the Precautionary Approach and the FAO Code of Conduct recommend the development of mitigation measures to

reduce or to avoid by-catches, even if the potential effects of these by-catches remain unknown. *Ad hoc* technological research aimed at reducing the amounts of by-catches by fisheries for tunas is thus a promising and recommended field of research.

The recent increase in the use of fish-aggregating devices (FADs) to catch tunas and billfishes is an increasing source of concern because of the small sizes of yellowfin and bigeye tunas taken in association with FADs and the relatively large by-catches. Additional research should be conducted on FADs in the various oceans. The goals of this research should include better understanding of the behaviour of the various species, the sizes of the fish associated with FADs, and determination of the effects, if any, of FADs on the movement patterns and biological characteristics of the fish.

Understanding and predicting how tunas and by-catch species respond to natural and fishery-induced changes is a major challenge for implementing an ecosystem approach into fisheries management. Innovative, large-scale, and multi-disciplinary ecosystem research and ecosystem modelling should be developed at an international scale. The aim of this modelling should be to evaluate better the potential effects on the tuna stocks and the pelagic ecosystems of area-time closures for selected tuna fisheries. The concept of closed strata appears to be promising in the context of the Precautionary Approach, but the potential impact of such management actions should be better evaluated through a comprehensive research program.

IMPLICATIONS FOR DATA COLLECTION AND STATISTICS

Current data collection programs do not all provide complete and accurate sets of data for determining the status of the stocks of tunas and tuna-like fishes, or the impacts of the physical environment and the species that share the habitat of the species in question. If the variations (or uncertainties) associated with each set of data are reported it would help in evaluating uncertainties in the results of the assessments.

Deliberate illegal, unregulated, and unreported fishing is a major source of concern in data collection, particularly since this can cause significant uncertainties in estimating the total catches. In addition, reluctance or incapacity of authorities to collect data and share available data with regional fishery bodies (RFBs) adds more uncertainties in the reported total catches. Failure to account for data coverage or quality, the use of different methods for recording weights or of inadequate size-frequency data where catches are reported in numbers, misidentification of species, and deliberate distortion of reports are common reasons for erroneous data. In logbook programs, the data source is the fishing industry and, while considerable effort can be put into minimizing misreporting and data entry errors, logbooks still record only information required by maritime authorities (locations and times) and activities which are important to the vessel owner, captain, and chief engineer. This usually results in logbooks recording activities associated with the taking of fish which are eventually landed, rather than all of those which are caught, nor on ancillary information required to standardize fishing effort, such as environmental data. Logbook and observer programs must be designed with full attention to data required to evaluate gear efficiency, including information on new technology, the environment, and incidental catches. Finally, implementing logbook systems with small-scale fisheries is frequently impossible. In such cases, a well-designed port-sampling system is necessary to collect the data at the desired level of resolution.

In sample-survey systems, uncertainty may come from inadequate records of fleet composition and activity or poor sampling design. Inaccurate fleet records often arise from systems that register fishing craft, but do not update registries on a regular basis: data on the inactivity of vessels or the removal of vessels from the fleet are not collected, leading to overestimates of fishing

effort. Market and consumer surveys rarely produce data that can be reliably used for stock assessment.

With adequate information on fleet composition and activity, logbook data can be treated as a valuable and extensive data sample of the activity of a particular fleet. The data that are collected can be raised to obtain estimates of the total catch and nominal effort, so total enumeration is not necessary. Much care is needed, however, in designing the stratification and sampling programs, and in estimating population level statistics. In suitable circumstances, electronic vessel monitoring system (VMS) reporting can be a reliable way to obtain information on fleet composition and activity and, in conjunction with port sampling, may, to a large extent, supplant logbook reporting as a primary data collection method. Issues of confidentiality appear to be the main constraint to the generalized use of this technology. These issues might best be addressed if monitoring were to be entrusted to RFBs, which, in general, have no enforcement mandate and may be trusted more readily by fishermen.

The RFBs can collect detailed data directly from the industry, or they may be able to obtain such data from national sources. If the data are from national sources, however, they will probably be coded to preserve the confidentiality of individual business enterprises. There are two disadvantages to obtaining the data from national sources. First, it is often necessary to have very detailed data, such as changes in the captains of the vessels, which would probably not be obtained from national sources. Second, the nations may use the records from industry for determining the amounts of taxes to be paid, in addition assessing the fishery, in which case false records may be furnished to the national governments. With constraints required for confidentiality in place at the RFBs, there is no confidentiality-based justification for the withholding of the fine level data needed for stock assessment. Furthermore, exchange of available data with and between RFBs will increase the data available to undertake stock assessments.

For other elements of uncertainty which cannot be quantified, well-designed sampling, tagging, and/or observer programs can provide means of improving data sets but, when these data are available, they should be used to adjust the estimates, rather than simply to quantify the errors. If sampling, tagging, or observer programs cannot be implemented, effort should be directed at improving the accuracy of the data obtained by other means.

While deficiencies in data programs are recognized, and there are ways to improve those programs, there are no universal solutions, so management agencies should carefully determine their research requirements, and, in turn, determine data priorities and cost implications.

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1 INTRODUCTION

This technical paper deals with the species of tunas and billfishes of greatest commercial importance. The tunas include skipjack, Katsuwonus pelamis, yellowfin, Thunnus albacares, bigeye, *T. obesus*, albacore, *T. alalunga*, Atlantic northern bluefin, *T. thynnus*, Pacific northern bluefin, *T. orientalis*, and southern bluefin, *T. maccoyii*, and the billfishes include swordfish, *Xiphias gladius*, Atlantic blue marlin, *Makaira nigricans*, Indo-Pacific blue marlin, *M. mazara*, black marlin, *M. indica*, white marlin, *Tetrapturus albidus*, striped marlin, *T. audax*, Atlantic sailfish, *Istiophorus albicans*, and Indo-Pacific sailfish, *I. platypterus*. There are many other species of tuna, and several other species of billfish, of lesser economic importance. When general statements are made concerning tunas or billfishes they do not necessarily apply to species other than those listed above. They are often referred to collectively as "tunas and tuna-like fishes" in this report.

1.1 Background

As the fisheries for tunas and tuna-like fishes have expanded during the decades since the late 1940s, regional fisheries bodies (RFBs) have been created to provide, at varying levels, for research and/or management of these resources, and for the ecosystems and species that are affected by the fisheries harvesting tunas and tuna-like fishes. These fisheries now extend throughout the tropical and temperate regions of the oceans and seas. The only area not covered at the time this report was written is the subject of the Multilateral High Level Conference to establish a regional fisheries body in the western and central Pacific.

In 1991, the Committee on Fisheries of the Food and Agriculture Organization (FAO) requested that FAO develop a Code of Conduct for Fisheries. Subsequently, FAO and the government of Mexico sponsored an International Conference on Responsible Fishing, held in Cancun in May 1992. Resolutions formulated in Cancun were presented at the United Nations Conference on Environment and Development (UNCED) in Rio de Janeiro in June 1992. The Rio meeting highlighted the importance of the Precautionary Approach in the Rio Declaration, and Agenda 21, Principle 15, of the Rio Declaration states that "*in order to protect the environment, the precautionary approach shall be widely applied by States according to their capabilities. Where there are threats of serious or irreversible damage, lack of full scientific certainty shall not be used as a reason for postponing cost-effective measures to prevent environmental degradation.*"

Several binding and non-binding agreements embodying the Precautionary Approach were developed and concluded during 1991-1996. The most comprehensive of these is the Code of Conduct for Responsible Fisheries, concluded in late 1995. The Code of Conduct addresses six key themes: fisheries management, fishing operations, aquaculture development, integration of fisheries into coastal area management, post-harvest practices, trade, and fisheries research. While a Precautionary Approach is integral to all the themes, it is applied particularly to fisheries management. Article 7.5, paragraph 1 includes *"States should apply the precautionary approach widely to conservation, management, and exploitation of living aquatic resources in order to protect them and preserve the aquatic environment."* The paragraph also provides that the absence of adequate scientific information is not a reason for postponing or failing to take conservation and management measures.

The Code of Conduct is a voluntary, non-binding agreement. However, it contains sections that are similar to those in the Agreement for the Implementation of the Provisions of

the United Nations Convention on the Law of the Sea of 10 December 1982 Relating to the Conservation and Management of Straddling Fish Stocks and Highly Migratory Fish Stocks which will, when it comes into effect, be a binding agreement (the UN Fish Stocks Agreement). These two agreements provide the formal basis for the Precautionary Approach to fisheries management.

The UN Fish Stocks Agreement has content and wording that is similar to the Code of Conduct, including those related to the Precautionary Approach and General Principles. The two Agreements incorporate the principal of reference points as important instruments for the application of the Precautionary Approach to fisheries management. Annex II of the UN Fish Stocks Agreement provides guidelines for the application of precautionary reference points. Paragraph 2 states, *"Two types of precautionary reference points should be used: conservation, or limit, reference points and management, or target, reference points."* Paragraph 5 stipulates, *"Fishery management strategies shall ensure that the risk of exceeding limit reference points is very low,"* and imposes the further constraint that target reference points should not be exceeded on average. Paragraph 7 states that *"The fishing mortality rate which generates maximum sustainable yield should be regarded as a minimum standard for limit reference points."*

The Expert Consultation on Implications of the Precautionary Approach for Tuna Biological and technological research originated from a recommendation of the Tuna Symposium sponsored by the International Commission for the Conservation of Atlantic Tunas (ICCAT) and held in Punta Delgata, Sao Miguel, Azores, Portugal, in 1996, which recognized the existence of similar problems in the implementation of the Precautionary Approach for tuna fisheries on the global scale. Because of these similar problems it is appropriate to consider research implications for tuna as a group.

The tunas and tuna-like fishes are highly-migratory species that are fished world wide, both in coastal and oceanic zones, and by multiple fishing gears. This large-scale distribution and the biology of these species are such that the scientific knowledge and uncertainties upon these stocks can hardly be compared with other species. These peculiarities of the tunas and tuna-like fishes and of the fisheries for them should be taken into account in the Precautionary Approach.

1.2 Proposed research or actions

The Precautionary Approach does not require that our knowledge of tuna stocks and fisheries improves before appropriate conservation and management measures are taken. It does, however, require that management measures be more cautious when information is uncertain, unreliable, or inadequate. The proper balance between acquiring knowledge and management action should be made objectively. On this basis, the output of the Consultation includes proposed research actions that elaborate the likely demands to characterize and reduce the uncertainties involved in the management of tuna fisheries. The Consultation considered how to take account of and describe the existing uncertainty in our understanding of the effects of fishing, and how the existing uncertainty might be reduced with appropriate research. Those two aspects are equally important for the application of the Precautionary Approach.

Under a Precautionary Approach, appropriately designed and implemented research can have direct benefits by reducing uncertainty, which may mitigate the problem. Conversely,

not conducting such research might require more restrictive management than would be needed with additional information.

The Consultation considered situations for which there are quantitative techniques for describing the effect of fishing and those for which there are few data and only qualitative information on the stock and the fishery. Any quantitative method of assessment should include estimates of uncertainty, and consideration should be given as to how uncertainty can be included in qualitative descriptions of tuna fisheries.

This report deals with both the target and by-catch species caught by the fisheries for tunas, and also with the other species that share the habitat of the tunas and tuna-like fishes.

As more and more species are targeted by fisheries in the world oceans, and as the capacities of the fishing fleets increase, it becomes necessary to consider harvesting strategies that take into account the interactions among species and environmental effects. With a reasonable knowledge of an ecosystem, it may be possible to determine management strategies that allow the utilization of resources in some optimal manner based on management objectives. When that information is not available for the pelagic-ecosystems, however, that approach is not possible. In this case, the Precautionary Approach suggests that the by-catches be maintained at sustainable levels or reduced. Further ecosystem research, based on an extensive collection of data on various important things, including by-catches, will then be urgently needed to provide scientific understanding of the effects of fishing on ecosystems.

The general acceptance of the need to consider the effect of fishing on ecosystems has not yet been expressed in practical management objectives analogous to those that have long been available for single species, such as optimizing catches subject to sustainability constraints. Until such objectives are developed, it will not be possible to give advice on how they can be met.

1.3 Uncertainty expected in results of tuna research

The Precautionary Approach can be followed regardless of the method of the assessment of the effect of fishing. For many of the stocks of the major market species of tuna, stock assessment is carried out via a quantitative model that estimates the response of the stock to fishing. Much of the Precautionary Approach described in the Code of Conduct and the UN Fish Stocks Agreement is based on this approach. However, there is not sufficient information available to do this for all stocks of tuna, and so less quantitative approaches (which at the minimum may simply be observing no signs of the effect of fishing at existing levels, e.g. the average size of fish or the catch rates are the same as at the initiation of the fishery) may be used.

Uncertainty in the results of stock assessment arises from observation error and model errors. Observation error includes errors due erroneous measurements or sampling errors. Model error may arise because of limitations in knowledge of the biology of the fish. Biological inputs to models include growth, mortality, longevity, reproduction, movements, stock structure, behaviour, and response to environmental conditions. Model error will also arise from an inability to model all the processes that affect the dynamics of a fish stock. Some of the uncertainty can be detected or measured through sampling theory, by lack of fit of the models, or by sensitivity analyses, and some may have to be assessed subjectively.

In addition, uncertainties associated with the implementation of management action must be considered when providing advice and assessments of associated risk.

Uncertainties may also arise from the use of new fishing technologies, whose effects could include changing the catchability of tunas, modifying the age distribution of those caught or killed, or modifying the environment and life history, which has been suggested as a possible effect of fish-aggregating devices (FADs).

1.4 Review of tuna biology

Tunas and tuna-like fishes exhibit several specialized biological characteristics that present challenges to stock assessment and application of the Precautionary Approach.

Tunas are pelagic fishes inhabiting a wide range of ecosystems in the upper layers of all oceans. Most of them are confined to tropical waters, where they live primarily above the thermocline in the upper 200 m of the water column. Although most tunas are hatched in tropical waters, the distribution of the adult feeding grounds varies among species–some are predominantly tropical in distribution, while others occur in temperate or subtropical waters.

To varying degrees, all tunas can thermoregulate, using a specialised countercurrent heat exchange system called a *rete mirabile*. The relative development of the rete determines how much each species can regulate its body temperature relative to the ambient water temperature. For example, yellowfin tuna, which are predominantly tropical in distribution, have a much less advanced rete than do bluefin tunas, which range from tropical to sub-polar regions. Using behavioural and physiological thermoregulation, bigeye and the bluefin tunas can also extend their vertical ranges to well below the epipelagic zone, diving to depths in excess of 500 m. In contrast yellowfin, lacking the advanced *rete*, are confined largely to the upper 200 m of the water column.

Tunas exhibit a strong schooling behaviour (at least in the earlier stages of their life, until maturity), a large spawning potential, and very rapid growth, especially in their juvenile phase.

Billfishes are also pelagic fish, inhabiting tropical and temperate waters. Swordfish, however, use an advanced thermoregulation system to make extended dives to depths of more than 800 m). They also make seasonal migrations in temperate latitudes, extending their range further into temperate waters as they grow larger.

As adults, all tunas and tuna-like fishes are high-level apex predators. However, their highly versatile and opportunistic feeding behaviour and ontogenetic changes in their feeding habits mean that over their life history tunas and tuna-like fishes occupy more trophic levels than almost any other group of fishes. Their high trophic level may have important implications on the ecosystem stability as a whole, should the levels of tunas and tuna-like fishes biomass change as a result of fisheries or environmental variation.

For most widely-distributed species, there are data that suggest genetic heterogeneity among ocean basins. However, there is little evidence to suggest that biological characteristics, such as growth, movements, natural mortality, longevity, spawning conditions, schooling and feeding behaviour, or environmental preferences, vary significantly among oceans. Although this may reflect the maturity of our understanding of many of these characters (*i.e.* not enough is known to make objective comparisons), it seems reasonable to

assume that observed responses of a species to exploitation in one ocean are likely to be similar to those in other oceans.

1.4.1 Characteristics of tropical and temperate tunas

All of the major market species of tuna spawn in warm waters. In broad areas of the equatorial and tropical oceans, it is common for the larvae of several species of tuna to be caught in single plankton tows. This sympatry breaks down as the fish reach the end of their first year of life.

The tunas can be separated into three general groups based on their distribution, general biological characteristics, and habitat.

Tropical tunas: Skipjack and yellowfin spend their entire lives in tropical waters, or tropical water transported into temperate latitudes by currents. They are characterised by small to medium maximum size, poorly-developed *retes*, rapid growth, early age at first maturity, year-round spawning, short to medium life spans (<10 years), and high production to biomass (P:B) ratios.

Temperate tunas: Northern and southern bluefin can be classified as temperate species. From as early as the end of their first year of life they spend the majority of their life feeding in temperate latitudes, but return to warm waters to spawn. They are characterised by large maximum size, well-developed *retes*, slow growth, late age at first maturity, seasonal spawning, long life spans (>15 years), and low P:B ratios.

Subtropical tunas: Bigeye and albacore tunas have several characteristics that suggest that they are intermediate between the tropical and temperate tunas. Although they are widely distributed in tropical waters as adults, both are also widely distributed in subtropical and temperate waters. Albacore are anti-equatorial in the Pacific and Atlantic Oceans. Both bigeye and albacore are characterised by intermediate maximum size, have moderately developed *retes*, relatively fast growth, first maturity at 2 or 3 years of age, seasonal spawning, intermediate life spans (10-15 years), and P:B ratios between those of yellowfin and the bluefins.

1.4.2 Stock structure and mixing rates

Despite considerable research on the genetics of tunas, using a wide range of methods, there is little evidence in most tuna species for genetic heterogeneity within oceans. The exceptions are yellowfin and albacore in the Pacific Ocean and bluefin and albacore in the Atlantic Ocean. The lack of evidence for genetic heterogeneity within oceans is generally thought to be a reflection of genetically-significant exchange rates (i.e. adequate exchange across ocean basins occurs in each generation to swamp genetic divergence). It is important to note that genetically-significant exchange rates can be in the order of a few individuals per generation. Thus, in the context of fisheries assessments and management, the lack of genetic evidence for spatial structure is uninformative, and should not be used as a basis for assuming fish are homogenous across an ocean basin.

Mixing rates within and among areas of interest (e.g. ocean basins, management areas, etc.) are more important in the assessment and management contexts. With the possible exception of the skipjack and yellowfin populations in the Pacific, we have inadequate understanding of mixing patterns and rates in tunas.

The fact that most species are broadly distributed has led some tuna scientists to hypothesize the presence of unexploited or lightly exploited areas. These areas, linked with a relatively high viscosity of the resources, may lead to a permanent unavailable fraction of the biomass (for example, in the Arabian Sea or the eastern Indian Ocean until recently).

1.4.3 Spatial distribution and movements

Spatial distribution

The populations of tunas and tuna-like fishes in all oceans occupy extensive areas (millions of square miles). Skipjack, yellowfin, and bigeye are ubiquitous in tropical oceans, and bigeye also occur in temperate waters. Albacore and bluefin spend most of their lives in temperate waters, but go to warmer waters to spawn. Swordfish are cosmopolitan and widely distributed in the oceans, and the adults typically migrate to temperate waters in the summer. Marlins are found throughout tropical and temperate waters, with seasonal latitudinal movements into temperate waters. Sailfish are distributed around tropical and subtropical waters, mainly in coastal waters, but also in oceanic waters.

Movements

Tagging studies have shown that all major species of tunas and tuna-like fishes are capable of large-scale movements (>1000 nm). The general patterns of movement vary significantly among species, and within species among different stages of the life history. For example, bluefin tunas are characterised throughout life by long-distance, directed migrations, while the movements of skipjack, despite their capacity to swim long distances, are usually more limited.

Most of what is known about the movements and migrations of tunas and tuna-like fishes is derived from conventional tagging and recapture experiments. As the distribution of releases and returns in most tagging experiments are restricted to areas in which commercial fisheries operate, these studies most often describe movements within or among fishing grounds, which are unlikely to be representative of the true range of movements or migrations of a species or population. Recent applications of archival and pop-up tag technology in tunas and tuna-like fishes have demonstrated some previously-undescribed patterns of movement and migration in these species, in particular cyclic migrations and seasonal movements into unfished areas.

Schooling behaviour

In the earlier stages of their life all tunas exhibit strong schooling behaviour. Schooling is less prevalent with increasing size in most species, except during spawning. Schooling fidelity is poorly understood in all species. Tagging studies have shown that individual skipjack tagged in the same school are often recaptured in separate schools shortly thereafter. However, tag returns for other species indicate that individuals may remain associated for periods of months to years. The relationship between abundance and school size may be particularly important to assessments that use catch rates.

Juvenile tropical tunas of different species, but the same size, are often caught in the same schools, but at larger sizes this is less frequent. The link between size and the extent of association among tuna species is very evident in the catches around FADs. A vertical heterogeneity (with juveniles on the top and adults at the bottom of the school) is also

frequently observed on both free-swimming and FAD-associated schools). Little information exists on the schooling behaviour of billfishes, although it has been observed that sailfish may occur in small groups.

Horizontal and vertical spatial heterogeneity

Both horizontal and vertical heterogeneityin the sizes of tunas have been observed. The surface fisheries that catch juveniles in surface waters, and the longline fisheries that exploit adults well below the surface, do not interact with one another simultaneously. Vertical heterogeneity among stocks may be important to consider in dealing with uncertainty.

1.4.4 Biological parameters

In general, despite assumptions of stability, few data exist on the variability of the biology of tunas or billfishes over time, or the extent to which key parameters vary geographically. Recent work on southern bluefin has demonstrated that the growth of juveniles has varied over a 30-year period, as a result of either environmental or density-dependent factors. Whether the same is true for other species should be investigated.

Longevity and natural mortality

Longevity varies significantly among the tuna species (Table 1). In many cases longevity has been estimated from tag return data.

Recent analyses of tagging data have provided evidence for large variations in natural mortality with size, the rates for juveniles being much higher (5 to 10 fold) than those for adults (Table 1). Estimates from tagging data have also indicated that the natural mortality is higher for the oldest fish of several species.

Estimates of the longevity of billfishes vary among species, although few age estimates are available. Little information is available on their natural mortality.

Growth

Growth is also highly variable among species (Table 1)--rapid for tropical tunas (skipjack and yellowfin), intermediate for bigeye and albacore, and slow for temperate tunas (northern and southern bluefin). Density-dependent effects seem to be common. Two-stanza growths have been observed for some species, from both otolith and tagging data, in the Atlantic and Pacific Oceans. Marlins and sailfishes have relatively rapid growth as juveniles (close to those of the tropical tunas), while swordfish grow more slowly, resembling the temperate tunas in this respect. Some tunas and tuna-like fishes, such as yellowfin, bigeye, and swordfish, have sex ratios that differ from 1:1 at large sizes, which could be due to differential growth or mortality.

Spawning and reproduction

High fecundity is characteristic of all tunas and tuna-like fishes, with females spawning several million eggs per year. All of the major market species of tuna spawn in warm waters. Tropical tunas spawn over wide areas, while bluefin have discrete spawning grounds in one to two relatively restricted areas.

Age and size at first maturity are variable (Table 1), from 1.5 year (45 cm) for skipjack to 12 years (147 cm) for southern bluefin. Spawning may occur throughout the year (skipjack) or during a limited period (2 months) for bluefin, with an intermediate situation for other tunas. Billfish spawning occurs in the warm tropical and subtropical waters throughout the year, with some seasonality at higher latitudes.

Recruitment

The spawner-recruit (S/R) relationship is generally poorly known, as estimates of the recruitment and spawning biomass are derived from catch data, which are not well suited for this purpose. For tropical tunas, the absolute levels of recruitment tend to be high, with relatively low variability among years (for instance in a 1:3 ratio between the highest and lowest recruitments). For the temperate tunas, the absolute recruitment levels tend to be lower. Long-term changes, such as cyclical (decadal) fluctuations and semi-cyclical (El Niño-Southern Oscillation (ENSO) events), due to environmental effects, have been often shown to influence the recruitment of both tropical and temperate tunas.

1.5 Management-related issues

1.5.1 Mandates for criteria and/or management objectives for the CCSBT, IATTC, ICCAT, IOTC and SPC

All regional tuna agencies represented at the meeting, except for the Secretariat for the Pacific Community (SPC), have management mandates. It should be noted, however, that a management arrangement for western and central Pacific tuna fisheries was being developed, with the Convention expected to be available for signature in August 2000.

The mandates and management strategies define the scope of the research and monitoring needed to address the Precautionary Approach for tunas and tuna-like fishes. The research includes stock assessment, ecological and biological characterizations of the fish and their environment, and the data collection and monitoring that are needed within that research to evaluating the expected performance of management strategies. If research is to help management in implementing the Precautionary Approach, then the management objectives (conservation constraints and targets) must be characterized adequately.

There are institutional differences in management objectives. For the Commission for the Conservation of Southern Bluefin Tuna (CCSBT) and Indian Ocean Tuna Commission (IOTC) the overall goals are to achieve "optimum utilization" and conserve the stocks. In a draft convention for the western central Pacific the goal is to achieve long-term conservation and sustainable use of the stocks. For both the Inter-American Tropical Tuna Commission (IATTC) and ICCAT, the stated general objective is to maintain stocks at levels that permit the maximum sustainable catch (yield). Within the constraints of their general goals, the agencies can also implement specific management plans to achieve shorter-term objectives. For example, both CCSBT and ICCAT have introduced plans to rebuild various stocks to given relative biomass levels by given years.

Table: Life history traits of selected tunas and tuna-like fishes

Species	Spawning duration (months)	Length at maturity (cm)	Weight at maturity (kg)	Age at maturity (year)	Max length (cm)	Max weight (kg)	Max age (year)	Juvenile growth ($\%L_{\infty}^{-1}$)	M Juveniles	M Adults	Min. SST (^{o}C)
Yellowfin	6	105	25	2.8	170	176	10	22.1	3.5 (30-40) 1.5 (40-50) 0.8 (50-60)	0.6 (60-70)	18
Bigeye	3	115	31	3.5	180	225	15	8.3	4.3 (<40)	0.2	16
Skipjack	12	45	1.7	1.5	75	23	4-5	40	9.0(<30) 5.0 (30-40) 2.0 (40-50)	1.5 (50-60)	20
Albacore	3	90	15	4.5	120	80	10	16.7			15
Atlantic bluefin	1.5	115	27.5	4.5	295	685	20	8.7			11
Southern bluefin	6	147	65	8-12	220	220	22-40	5.6	0.22-0.29	0.1	9

Table: Life history traits of selected tunas and tuna-like fishes (continued)

Species	Spawning duration (months)	Length at maturity (cm)	Weight at maturity (kg)	Age at maturity (year)	Max length (cm)	Max weight (kg)	Max age (year)	Juvenile growth ($\%L_{\infty}^{-1}$)	M Juveniles	M Adults	Min. SST (°C)
Atlantic little tuna	12	42	-	1.5	85	12	6	32.9			18
Swordfish	3	175	70	5	290	650	17	12.1			15
Atlantic white marlin	4	130	20	3	260	-	15	16.7			20
Atlantic sailfish	2	130	16	3	255	-	18	17			22

Spawning duration: number of months per year during which spawning occurs.

Length, weight, and age at maturity: from literature.

Maximum length, weight and age: maximum length and weight from catch-at-length data collected during historical period (99% of distribution); maximum age from tagging (time at liberty + estimated age at release). (For southern bluefin the maximum age was estimated using hard parts, the maximum observed from tagging is 22 years).

Juvenile growth: means juvenile growth as a percentage of the maximum length (100*[length at maturity/maximum length]/age at maturity; **M** for yellowfin, skipjack and bigeye from tagging by the SPC.

Minimum SST: from literature.

The focus of the Consultation was on the implementation of the Precautionary Approach in the context of international tuna management and RFBs. There may be other areas of interest or requirements for management at more local levels.

1.5.2 Review of Precautionary Approaches in other bodies with respect to research implications

It is beyond the scope of this Consultation to review the frameworks that have been proposed by various international or national agencies for the implementation of the Precautionary Approach. Of more direct relevance to our Terms of Reference is the fact that all such agencies have highlighted the need for strengthened research due to either one of the two reasons. First, the international agreements call for increased monitoring and research in cases of large uncertainty (or data-poor situations). Second, as the Precautionary Approach calls for increased conservatism in the face of higher uncertainty, there are obvious benefits to be gained by investing in research that results in cost-effective reductions in uncertainty.

For example, it was concluded in the Report of the Eleventh Meeting of the Standing Committee on Tuna and Billfish (Honolulu, Hawaii, May 28-June 6, 1998) that: *"The current levels of funding support for data collection, research and stock assessment of tuna fisheries of the western central Pacific are insufficient (< 1% of the value of the catch). Funding support will need to be increased substantially to allow management of this valuable fishery to be guided by good science. ... One response to [this] uncertainty is to reduce catch or fishing effort in order to reduce the risk that a limit or target reference point is exceeded. A second, longer-term response to uncertainty is to reduce it by investment in carefully targeted data collection and research."* Similarly, it was stated in the Report of the Meeting of the ICCAT Ad hoc Working Group on the Precautionary Approach (Dublin, Ireland, May 17-21, 1999) that: *"Information underpins the precautionary approach, given that more caution is required when information is uncertain. In order to achieve an adequate balance between resource usage and precaution, increased funding at all levels (data collection, analysis, monitoring and enforcement) may be necessary,"* and went on to provide specific recommendations aimed at improving the data or knowledge base used in its stock assessments.

1.5.3 Definitions of concepts

This section provides definitions of some key terms as they are used in this report. The list of definitions is not meant to be exhaustive.

Reference points are benchmarks against which an estimate about the stock can be measured, in order to determine its status and guide fisheries management. Two types of reference points are identified in the UN Fish Stocks Agreement. *"Limit reference points set boundaries which are intended to constrain harvesting within safe biological limits within which the stocks can produce maximum sustainable yield. Target reference points are intended to meet management objectives."*

Stock status is typically determined relative to two dimensions. One, is on a scale related to an **overfished** state, which means that the biomass (or an appropriate index of biomass) is "too low," i.e. below the biomass limit reference point that has been set as a benchmark to define the state of being **overfished**. The other dimension is on a scale related to the act of **overfishing**, which means that the fishing mortality rate (or an appropriate index of it) is "too high" relative to the relevant fishing mortality reference point. For a healthy

stock, continued overfishing is expected to result eventually in an overfished state. For an overfished stock, continued **overfishing** represents an even greater risk of stock collapse.

The concept of **risk** due to **uncertainty** is fundamental to the implementation of the Precautionary Approach for fisheries management. In the context of the Precautionary Approach, risk has been as the "probability of something bad happening." In its guidelines for the application of reference points, the UN Fish Stocks Agreement states that "Fishery management strategies shall ensure that the risk of exceeding limit reference points is very low." An element that is shared by the various agencies that are developing frameworks for the application of the Precautionary Approach is that the definition of what "very low" means should be provided by fishery managers. However, it should be noted that, depending on the limit being considered and the life history characteristics of the stock in question, the biological consequences of exceeding the limit by a given amount may differ substantially. For this reason, the various agencies also consider that it must be scientists who provide the managers with adequate information so that they can, in turn, make informed decisions about acceptable levels of biological risk.

A **management strategy** encompasses the entire set of actions designed to achieve the goals of management. According to the UN Fish Stocks Agreement, *"Fishery management strategies shall ensure that the risk of exceeding limit reference points is very low. If a stock falls below a limit reference point or is at risk of falling below such a reference point, conservation and management action should be initiated to facilitate stock recovery. Fishery management strategies shall ensure that target reference points are not exceeded on average."* A **control rule** is a way of expressing actions to be taken under a management strategy, depending on the status of the stock. A type of control rule that has been proposed incorporates limit and target reference points into a scheme that shows how fishing mortality rates should be set, depending on the estimated biomass level. It should be noted, however, that the actual implementation of management actions is not achieved by setting a fishing mortality rate, but rather through fishery **controls**, such as effort limitation, catch quotas, closed areas or seasons, etc. Uncertainty is present in each of the many steps involved between the design of a management strategy and its actual implementation.

1.6 Structure of this report

Research into issues related to the management of tunas and associated species was considered under four headings, stock assessment, biological and environmental research, and data collection and fisheries statistics. Most of the implications of technology research are also issues for the other three areas, so they are included in the chapters dealing with stock assessment, biological and environmental research, and data collection and fisheries statistics. Stock assessment is treated first, as it is the theme most directly linked to management. Biological and environmental research, and data collection and statistics support stock assessment. To some extent the scope of work in each area depends on requirements from those considered previously in the report.

2 IMPLICATIONS FOR STOCK ASSESSMENT OF TUNAS AND ASSOCIATED SPECIES

2.1 Description of possible fishing management regimes and the implications for stock assessment research

The goal of any fishing management regime is to control fishing mortality rates in order to achieve management objectives and to maintain the fishery within management constraints. The particular objectives and constraints chosen by managers imply that certain research and monitoring activities be addressed so that scientists may evaluate the effectiveness of the management and predict the likelihood of alternative future management outcomes. One subset of these objectives and constraints includes those associated with Precautionary Approaches of management. These impose some specific research needs for stock assessments and monitoring.

2.1.1 Control rules

One way to characterize precautionary management regimes is through **control rules**. A control rule describes a variable over which management has some direct control as a function of some other variable(s) related to the status of the stock. In other words, the control rule represents a pre-agreed plan for adjusting management actions, depending on the condition of the stock. In broad terms, the management actions may be designed as strategies to achieve a variety of socio-economic and conservation objectives through imposing (1) a particular exploitation rate (to harvest a specified fraction of the stock each year), (2) a particular escapement (e.g., to maintain a specified spawning stock size), or (3) a particular catch limit. A control rule does not have to adhere strictly to any of these three strategies: managers may choose to have a mixture of these strategies, or they may prefer control rules that achieve different results, depending on the condition of the stock.

In the case of Precautionary Approaches to management, however, there are some specific requirements that are typically imposed. There is the need for criteria for determining the **overfished** status of the stock (i.e. a stock level under which the stock would be classified as overfished) and criteria for specifying **overfishing** (i.e. a rate of fishing that would eventually reduce the stock to an overfished state). Once these limits have been established by management, a control rule might, for example, be a feedback rule in which fishing mortality rate is a declining function of stock biomass as that biomass approaches or falls below some **overfished** level.

Control rules can be defined in terms of limits (conditions to be avoided) and in terms of targets (objectives to be achieved). It is important, however, to acknowledge the role of uncertainty in developing both limit and target control rules. Controls (or, indeed, any management action) cannot be imposed perfectly. There are estimation errors in the status of the stock and in the overfishing or overfished criteria themselves. There are also errors in how broad scientific measures, such as fishing mortality rate, are translated into actual fishing effort or into allowable catches. There are also natural variations in the population dynamics of the stock. In addition, there are implementation errors when regulations are not fully imposed or fully adhered to. Hence, there are practical difficulties in defining targets and limits: one would expect that due to these sources of variation measured status would be above the target half the time and below it half the time. Thus, if the limit is defined as being too close to the target, then there may be an unacceptably large probability of exceeding the limit, just due to the variation associated with trying to achieve the target. In any case,

though, the responsibility of the research and assessment process is to evaluate these uncertainties and to make the most appropriate determinations of the probability that the targets are being achieved and that the limits are being avoided. Precautionary actions may be taken by management, based upon its understanding of the risks and implications of these probabilities.

Precautionary limits and targets are a component of the overall management objectives and constraints. Indeed, there are multiple objectives for management, such as maximization of catches, stability of catches over time, equitable distribution among users, and maintenance of market supplies. There will always be tradeoffs between objectives and constraints, including those associated with precautionary criteria, which should be evaluated. Also, Precautionary Approaches per se do not eliminate the possibility of developing new fisheries or new entrants into existing fisheries. If the research and assessment is expected to respond quickly and appropriately to these events, however, then there is an obligation to collect data to do that. In particular, there is a need for timely information in a developing fishery, so that management can respond as status measurements evolve.

While *ad hoc* approaches to management may be effective when applied by judicious managers, they limit the usefulness of scientific evaluation: one cannot predict in advance how effective management will be relative to the limits and targets, and effects of the decisions may be cumulative. In its guidelines, the UN Fish Stocks Agreement *states "reference points shall be used to trigger pre-agreed conservation and management action."* This does not need to be interpreted strictly as management requiring a control rule approach, as implied by FAO's 1996 technical guidelines on the Precautionary Approach to Capture Fisheries and Species Introductions: These guidelines *state "scientific evaluation of management options requires specification of operational targets, constraints and decision rules. If these are not adequately specified by managers, then ... analysis requires that assumptions be made about these specifications, and that the additional uncertainty resulting from these assumptions be calculated. Managers should be advised that additional specification of targets, constraints and decision rules are needed to reduce this uncertainty."* The scientific role in developing rules is one of continual monitoring, re-evaluation, and testing. The scientific knowledge evolves, management objectives change in accordance with the political context, and socio-economic factors are dynamic.

Thus rules, whether they are simple or complex, should be regularly evaluated and tested, based upon the desired management features.

Testing should include performance testing through simulations using an appropriate range of alternative hypotheses. Typically this is done by creating an operating model, i.e. a simulation of the underlying population and fishery dynamics and the fisheries data that are derived from it. Then this simulated fishery system is assessed with the stock assessment model that is being used. Predictions of performance measures are made, assuming the management control rules are implemented. Many iterations are carried out, using alternative inputs and hypotheses for the operating model. For example, a test of an alternative hypothesis might be: how well does the rule perform when the underlying natural mortality rate is different than that assumed? It is important that the operating model be created in sufficient detail and that relevant alternative hypotheses be examined. Otherwise, the test results may be misleading.

The implicit scientific obligations to precautionary management approaches are to determine status relative to limits and targets, to predict outcomes of management

alternatives for reaching the targets and avoiding the limits, and to characterize the uncertainty in both of these.

Additionally, it is incumbent on the scientists to assist managers in prioritizing the research investment to reduce that uncertainty.

2.1.2 Recovery plans

Recovery plans are required when limits have been exceeded and the stock is in an overfished state. Recovery plans are essentially schedules of actions to improve the stock so that an overfished limit is no longer being exceeded and that subsequently the target is being achieved. Implicit in a recovery plan, in addition to the targets and limits, is specification of the recovery period and the recovery trajectory.

Despite having a well-planned schedule and trajectory, recovery is not guaranteed. Ecological shifts in communities or oceanographic variability may limit both the productivity and the potential of a stock to achieve the recovery goal. Under present knowledge, these sorts of dynamics are not predictable. Thus, there is inherent uncertainty in the trajectories.

The duration of recovery is the time until the status measure, for example the spawning biomass, increases above the limit and on toward the target. Specification of the desired duration of a recovery period is a management prerogative. However, there are some scientific constraints. The recovery period should be long enough to allow an acceptable probability that the status measure(s) exceed the rebuilding limit and target, given the productivity of the stock. If the period is too short, recovery may not be feasible even with no fishing. Basic life history information for, for example, temperate versus tropical tunas, coupled with stock projections with zero fishing, should provide guidance on this. Long-lived species have less annual growth potential, and this should be noted in specifying recovery periods. Biological information on stock productivity should define whether a recovery period is infeasible.

It is more difficult to supply scientific criteria when a recovery period is too long. Suffice it to say that if the period is very long, then the risk of a stock being in an overfished condition becomes increasingly less certain due to uncertainties about future recruitment, and science cannot offer much guidance.

Research is needed to characterize the risks and uncertainties associated with long-term projections.

Recovery trajectories are essentially the specification of the interim management objectives during recovery. For example, do managers want to have large immediate reductions in catch to increase the probability of more rapid stock increases, or do they want to phase in reductions with concomitant slower short-term recovery? There are an infinite number of combinations on recovery themes that managers may supply.

For scientific evaluation there is a need for interim milestones, i.e. some interim goals that can be examined so that the performance of the recovery plan may be evaluated and, if necessary, adjustments can be recommended.

In addition, it is important that the timing of these interim milestones is concordant with the basic life history and population dynamics of the fish and with the scientists' ability to

measure changes. For example, if the interim milestone were scheduled every three years for a temperate tuna, then that may imply that there should be a research investment in the monitoring of trends in abundance of juveniles in order to detect the response to management.

An essential responsibility of stock assessment research with respect to recovery plans is the determination of feasible trajectories, the evaluation of the uncertainty under various management trajectory scenarios, and the re-evaluation of performance as the plan progresses.

2.1.3 Communication

Communication of the results of the stock assessment analyses to managers, fishermen, and others is an important step in the Precautionary Approach.

While the exact form of that communication will depend on circumstances, three principles should be considered when developing communication channels: (1) the presentation of results should be transparent, so that the process by which the results were achieved could be traced and duplicated; (2) the presentation should be informative, especially with respect to the likelihood that limits and targets will be exceeded; and (3) the presentation should be simple enough that it can be easily understood.

When actually preparing communications, one will inevitably have to make tradeoffs on these three principles, according to the audience receiving the results, particularly in regard to the details of transparency. Obviously, not all members of the audience will want to know all the intricacies of an analysis. However, they should be confident that such detail is available and that the detailed reports can be reviewed. Additionally, reports should convey the sources of uncertainty that are included within the analysis and those that are not. This suggests that communication will be in multiple forms, including reports and briefings, to name just two. These principles should provide a basis for communication.

2.1.4 Research links

The implementation of precautionary management approaches suggests important research links with stock assessment processes. It is important that the fisheries be monitored in terms of evaluation of management performance, incorporating evolving changes in management objectives and evaluating management performance relative to interim milestones in recovery stocks. Underlying all of these is the need for measurable limits and targets, the need to characterize uncertainty and to guide the investment priorities to reduce that uncertainty, and the need for operational testing of both estimation models and management schemes.

Because of the similar nature of tuna stocks and tuna fisheries in the different oceans, there is the need for closer collaboration among scientists and RFBs involved with tuna stocks of different oceans.

The nature of the stock assessment approaches is discussed in the subsequent section.

2.2 Stock assessment models

Assessment models represent the essential framework to integrate the information coming from different sources and to produce estimates of reference points and current statuses of the stocks. Furthermore, they have been used for many years for many tunas and tuna-like fishes and, therefore, many advantages and shortcomings have been examined.

2.2.1 Characteristics of tunas and tuna-like fishes as they relate to stock assessment models

Some of the characteristics of tunas and billfishes pose specific complications to the monitoring and assessment of their stocks. Descriptions of the biological and environmental characteristics of these resources are given in Sections 2.4 and 4.2, and other features are discussed below.

Catch rates: Because the fisheries evolve rapidly, utilize different gears, and take place in different areas, catch rates tend to provide snapshots of the relative abundance of particular size ranges in particular areas at particular times of the year. Factors that affect the vulnerability of the fish to capture, such as schooling behaviour, vertical movement, and variations in oceanic conditions, also complicate interpretation of catch rates. Putting together global indices of abundance, using fishery-independent surveys, would, in most cases, be prohibitively expensive.

Fleet dynamics: The mobility of industrial fleets allows them to change their areas of operation as needed to maximize their profits. They often develop new fishing strategies and tactics, such as deployment of new types of gear, modifications of current types of gear or they way the gear is used, and changes in the patterns of cooperation among fishermen. It is often difficult to account for or assess the effects of these changes.

Life history: In addition, there are differences among tunas that affect the stock assessments. In temperate tunas (see Section 2.4.1) the long life span, combined with a late maturity, often causes a lag in reaction time of a stock to management measures taken.

2.2.2 Model types

In terms of data requirements and outputs, a useful distinction can be made between age-aggregated and age-structured models. These two categories comprise the vast majority of assessment models currently used. Age-aggregated or production models characterize the response of an aggregated property of the population, typically biomass, to exploitation. Age-structured models contain an internal representation of the age-structure of the population and how it progresses over time in response to exploitation. More recent extensions of both types of models have included spatial structure and environmental heterogeneity. These approaches are promising, but require detailed information on the movements of the fish.

There a relationship between the type of models applied to the assessment of a species, the management targets and constraints, the amount and types of data available, and the characteristics of the biology or the fisheries associated with that species. For example, the difficulty in determining age in skipjack tuna and the fact that it has extended spawning period complicate the application of age-structured models for these stocks and, therefore, production models have more often been used.

These models differ in a significant way in their data requirements and the outputs that they provide. Production models require knowledge about the removals from the population and one or more measures of relative abundance. Typically, a time series of several years of catch and effort data is used. The parameters of these models can be easily cast in terms of useful reference points, such as the coefficient of fishing mortality, F_{msy}, and biomass, B_{msy}, corresponding to the maximum sustainable yield.

Age-structured models require, in addition to information on the catches of the different fisheries involved, data on the size composition of the catch, some way of converting the size data to age data, and one or more indices of abundance. Typical outputs include a matrix of abundance at age (or size) and one or more vectors of selectivities at age. In this case, the estimation of the MSY-related reference points is not as direct as in the case of some production models, and it requires some additional assumptions the about stock-recruitment relationship. However, as will be discussed later, the simplicity of the production models comes at the price of more restrictive structural assumptions.

An assumption common to both types of models is that some or all of the parameters measuring productivity of the population are stable over time. This stability assumption, which may often be violated, affects the ability of the assessment to predict future outcomes, e.g. in projections from age-structured models.

Production models

Production models have a long history of application in tuna fisheries, primarily because they typically require only catch and effort data and because of the easy translation of its parameters to quantities relevant to management. Some of the first tuna stock assessments were done using these models.

These models, however, do not always approximate well the responses of a population to exploitation. For example, production models do not incorporate the time lag associated with transient states in the age composition of the population when the exploitation rate changes. This problem has a greater effect on the analyses of species with long life spans, and could be alleviated by the application of variations of these models, such as delay-difference or age-structured production models that address this problem.

Perhaps more critical are the stability assumptions implicit in most production models. For example, they usually assume a vector of age-specific selectivities that is invariant in time. It is important to note that, in this context, selectivity should be considered the result of not only gear selectivity, but also of particular fishing strategies (i.e. the choice of fishing areas and/or seasons). This stability assumption can be frequently violated in tuna fisheries in which there have been significant changes in fishing strategies, such as the development of a FAD-associated fishery).

A similar problem occurs when a regime shift in environmental conditions affects the productivity of the population, compounded by the difficulty in detecting such shifts.

In these cases the problems might be reduced by introducing a time series structure in the relevant parameters (e.g. carrying capacity or catchability), allowing them to change slowly with time. Parameter estimation may require the use of auxiliary environmental data.

In any case, the consequence of violations of these assumptions is that, if the changes are significant, reference points would have to be recalculated, since they are conditional on the assumption of constant productivity.

Age-structured models

This category of models can be further divided into models that contain a statistical error structure (e.g. separable models) and those that do not exhibit this feature (e.g., virtual population analysis (VPA) models). Models with a statistical error structure facilitate the estimation of some of the components of the uncertainty surrounding an assessment and carrying that uncertainty throughout the analysis.

As a general principle, one of the implications of the application of the Precautionary Approach is that preference should be given to models that offer a formal framework to represent uncertainty and to evaluate alternative hypotheses in the assessment.

The estimation procedure in models with a statistical error structure is based on the comparison between values predicted by the model and values observed in the fisheries.

In general, whether these models are structured on the basis of age or length, they should be able to produce predictions of measurable quantities, such as length composition of the catch, for the purpose of estimation of parameters, rather than of quantities that have not been directly measured, such as catch-at-age estimation by cohort slicing.

A common practice in age-structured models is to aggregate the oldest age categories into a "plus group" because of the difficulties in discriminating age classes solely from the length distributions. The number of age classes thus grouped can be significant when the population has a long life span and most of the individual growth takes place early in the life of the fish. In some cases, the dynamics of the plus group cannot be well represented by the model, as when the age-specific selectivities are changing within the plus group. In these cases direct ageing is a valuable tool in disaggregating the plus group, thus avoiding this problem.

Age-specific natural mortality rates may be explicit input parameters required in age-structured models. In general, there is little information with which to estimate these, and this can be a major source of uncertainty in assessment advice.

Length-frequency data might be more informative with respect to growth at a spatial scale smaller than the entire stock range. In other cases, incorporation of spatial structure makes it possible to investigate assumptions regarding stock heterogeneity, a key issue for highly-migratory species.

2.2.3 Measures of abundance

An important requirement of many of the analytical tools discussed above is the availability of a relative or absolute measure of abundance or fishing mortality. Again a useful distinction can be made between the measures of abundance derived from data available on the operations of the fisheries (fishery-dependent indices) and those obtained from fishery-independent data.

Although there are many reasons to prefer a fishery-independent measure of abundance, in practice, most current stock assessments of tunas depend on indices derived from catch and effort data. This is due, in part, to the prohibitively large cost of obtaining measures of abundance that sample adequately the population ranges of tunas and tuna-like fishes. Therefore, statistical methods for standardization have been developed to address such things as spatial structure to the extent that the data allow.

Fishery-dependent measures

The principal assumption behind the classic use of catch-per-unit-of effort (CPUE) as an index of abundance is that there is a linear relationship between standardized CPUE and the abundance of the stock. The many ways in which this assumption can be violated have been discussed and documented. For example, if the degree of mixing of the population were low compared with the exploitation rate in a given location, the CPUE would reflect a local depletion rather than the global relative abundance of the population. Additionally, dynamics of the fishing fleet can alter the degree of sampling coverage.

An important and frequent problem is that unquantified increases or decreases in catchability can lead to an overly optimistic or pessimistic appraisals of the trends in population size. To some extent, standardization of the effort alleviates some of these problems but, unfortunately, the information required to effectively estimate these changes in fishing power is rarely available. One alternative is to replace the assumption of constant catchability in the assessment models by the assumption that the catchability changes slowly over time and allow those changes to be estimated. The incorporation of additional information, such as tagging data or effective fishing power, can help in these structural time-series approaches. In another approach, alternative scenarios can be considered under the assumption of a non-linear relationship between CPUE and abundance.

Technological changes leading to potential changes in fishing power should be properly documented and data should be gathered in order to assess the actual impact on catchability.

For example, the changes in fishing strategies brought about by the FAD-associated purse-seine fisheries will require careful consideration of alternative measures of effort, possibly on the basis of new data, in order to obtain meaningful indices of abundance. In another example, the role of fishing depth in the analysis of longline fisheries will also require more analysis. Furthermore, scientists may be unaware of some technological changes due to the proprietary nature of the activity. A good working relationship with the industry is important in this respect.

Alternative scenarios to account for the problems in interpreting catch rates as indices of abundance must be incorporated into the evaluation of uncertainty.

Fishery-independent measures and scientific experiments

Perhaps the most important source of a fishery-independent measure of abundance for tunas and tuna-like fishes is tagging data, although, strictly speaking, it also depends on the fisheries for the recovery of the tags. Tagging can produce many kinds of useful information, such as estimates of absolute abundance, natural and fishing mortality, and growth, and data on movements of the fish. It is important to consider carefully the design of an experiment in order to maximize its benefits. For example, there are definite statistical advantages to tagging fish of several cohorts, and tagging fish of each cohort more than once during the

period of its existence in the population. It is preferable to carry out the analysis of tagging data within the framework of an integrated assessment model.

The use of tagging data requires knowledge about tag shedding and reporting rates and the rate of mixing of the tagged and untagged components of the population. Tag shedding can be estimated through double-tagging experiments and reporting rates by tag-seeding studies, although the value of the latter may be questionable. The assumption of mixing becomes less restrictive if spatial structure is incorporated into the model, so that mixing is required only within each spatial stratum. Large numbers of fish released at the same location at the same time are sometimes recaptured by one vessel a few days later, before they have had time to mix with the untagged fish in the vicinity. In such cases it may be necessary to disregard data for fish that were at liberty only a short time.

Recently, there have been technological advances in tag design, such as archival tags and pop-up tags. At this stage the information that such tags provide is more useful for generating hypotheses on tuna behaviour, including movement, for the purpose of interpreting catchability or alternative model structures than it is for providing estimates of fishing mortality or measures of abundance.

Fishery-independent surveys, e.g. research-vessel and aerial surveys, do not often provide useful information, mainly because of the characteristics of tunas and tuna-like fishes. The extended range of these populations, even when they aggregate for spawning, means that the surveys can cover only a representative fraction of the total area of distribution. In some cases, they can provide only minimum estimates of abundance. Nevertheless, more recent model developments allow the use of measures of some portions of the stock, such as particular age groups or a specific area. Thus, partial surveys can still be useful.

In any case, it is necessary to ensure that appropriate consideration is given to the design of the survey. It is also necessary to consider whether the reduction in uncertainty to be expected from the survey justifies the costs associated with it.

2.2.4 Stock-recruitment relationships and projections

Assumptions about stock-recruitment relationships are particularly critical to the ability of projections to produce useful predictions. Unfortunately, characterizing the uncertainty in model structure and model parameters in the prediction of future recruitment is, in practice, very difficult. For example, the assumption of stability in the stock-recruitment relationship might be violated if there is a major shift in environmental regimes. The occurrence of such shifts usually cannot be predicted, and they are difficult to detect from data. Similarly, changes in the age-specific selectivities can occur as a result of changes in the pattern of exploitation by the fisheries involved.

In some cases, the short time series of data available for estimating a stock-recruitment relationship affects the perception of what could be a reasonable function involved, as the range of observed spawning stocks might be too restricted.

Projections are a standard tool in extending the results of the models to assess the probabilities of various outcomes within specified periods. They require estimates of the most recent population structure and some assumptions about future recruitment and the evolution of the fishery.

These difficulties result in projections that become increasingly unreliable as the length of the period for which the predictions are made increases. In most cases, therefore, only short-term projections are likely to be reliable, as they will depend less on the assumed stock-recruitment relationship.

Projections under certain types of management scenarios might be more variable than others. For example, constant catch scenarios might result in more variable projections because they do not include consideration of future gains in information in light of management responses.

2.2.5 Empirical methods

It should be noted that the modelling framework described above has been developed for a situation for which adequate data are available to estimate a set of reference points with a specified level of confidence. Stocks could be characterized as data-rich, data-moderate, or data-poor, based on the type, amount, and quality of the data and the degree to which they are informative about stock dynamics.

In data poor-situations, the United Nations Convention on the Law of the Sea Relating to the Conservation and Management of Straddling Fish Stocks and Highly Migratory Fish Stocks guideline indicated that *"provisional reference points shall be set,"* and that *"the fishery shall be subject to enhanced monitoring so as to enable revision of provisional reference points as improved information becomes available."* In such cases empirical methods, such as indices of trends or stability of the catches, trends in CPUE, average size, or age or length composition may be useful indicators of stock condition. Empirical methods, by their nature, however, rely on strong assumptions about the stocks and the fisheries that are not always explicit. These assumptions should be expressed and evaluated. Simulation-based performance evaluations are recognized as useful tools to examine empirical status indicators, helping to judge their robustness, representativeness, and reliability. They may also help to determine sources of uncertainties and prioritize the research needs. It should be noted, however, that the performance of simulation-based models depends largely on model structures and selection of hypotheses.

While performance and reliability of the indicators can be improved through feedback from the realized situation, empirical methods should not be construed as long-term substitutes for appropriate stock assessment methods.

2.3 Ecological and environmental issues in stock assessments

The environmental and ecological factors affecting tunas and tuna-like fishes (including by-catch issues) are discussed in Sections 4.3 and 4.4. For purposes of stock assessments, there is a need for operational definitions of objectives for ecosystem and/or by-catch management.

2.3.1 By-catches and stock assessment

Assessments of by-catch species in fisheries directed at tunas and tuna-like fishes are difficult for several reasons. Although single-species methods are still applicable, there are practical limitations because of the lack of data. In order to have the data to perform single-species assessments of by-catch species, the level and kind of sampling and, indeed, the information on the general life history patterns of the organisms being sampled would have to

be similar to those being conducted for the tunas and tuna-like fishes. Nevertheless, estimating trends in the CPUEs may be useful for monitoring changes in the abundances of by-catch species.

By-catch species are often caught by fisheries other than those directed at tunas and tuna-like fishes. Accordingly, collection of data for all the important fisheries is necessary, for which collaboration between national organizations and the RFBs will probably be required.

The precision and accuracy of standard fisheries models is conditional, to some extent, on fishing mortality being a significant proportion of total mortality. If a by-catch species is rare, or if it is abundant, but occurs infrequently in the catch, then the applicability of standard fisheries models may be questionable. Fisheries-independent surveys may be useful for estimating relative abundance, but they would usually be expensive.

2.3.2 Environmental issues in stock assessments

Environmental impacts on the dynamics of tuna stocks are known to occur in all regions. These may be on seasonal, interannual, or decadal time scales, and may affect such biological processes as recruitment, natural mortality, growth, movement, and vulnerability to capture. Depending on the complexity of the stock assessment model being used, such effects might be detected specifically on such processes, or in aggregate form as changes in productivity or carrying capacity.

It is possible that environmental effects on shorter time scales could be incorporated to some extent as process error in stock assessment models. Where such effects are significant but not accounted for, the ensuing model mis-specification may result in more variable and/or biased results.

Long-term environmental variation that results in a significant change in stock productivity may require a direct management response. For example, where there has been a long-term, environment-driven change in recruitment, a biomass-based limit reference point that is expressed as a certain percentage of the average virgin biomass may require re-calibration to the current average recruitment levels. If such re-calibration does not occur, the management targets may be unrealistic under the changed stock conditions.

Additional research is needed to establish criteria for re-calibration of reference points to address regime shifts.

As research develops on the relevant factors important to ecosystem management (see Section 4.4) and management goals for the ecosystem are specified, modelling research will still fit into the control-rule framework of monitoring, evaluating performance, and revising of the models. Whatever form these goals might take, for the foreseeable future the modelling is likely to generate empirical approaches for evaluating progress.

2.4 Uncertainty analysis

The need to provide analyses of the uncertainty associated with the provision of scientific advice is embedded in the Precautionary Approach. In addition, the guidelines in the UN Fish Stocks Agreement for the application of the Precautionary Approach require assessments of the risk of exceeding reference limit points. As such, it is not sufficient to

simply provide single "best "estimates of the status of a stock with respect to reference points and predictions about the future consequences of management actions, as estimates of the associated uncertainty, e.g. variances and potential biases, are needed.

Quantification of the uncertainty associated with the estimates of the status of a stock relative to a specified reference point is complex, and there is an urgent need for research to improve and develop the mathematical techniques for doing this.

The complexity arises because of the variety of data sources, the numerous inputs required, and the limits of knowledge about the underlying process.

2.4.1 Sources of uncertainty

Uncertainty has two components, accuracy and precision. The following is one way of characterizing the uncertainty that leads to estimation error in stock assessments:

- Observation error
  - Measurement error (e.g. uncertainty associated with individually-measured quantities, such as weight or length, or weight of the catch);
  - Sampling error (e.g. uncertainty associated with having obtained data from a sample of the catch or of the fleet);
- Modelling error
  - Input parameter error (e.g. uncertainty associated with parameters, such as natural mortality, required in the assessment models);
  - Model mis-specification error (e.g. uncertainty associated with the underlying model structure and assumptions, such as the form of the stock-recruitment relationship or assumptions of independence).

In addition, when evaluating the risk associated with future management actions, implementation uncertainty (e.g. the possibility of "high-grading" (continuing to fish after the boat is loaded or a limit has been reached, and discarding the fish caught previously which are less valuable than the ones just caught)) needs to be considered.

There are two issues that should be highlighted with respect to uncertainty created during the step that goes from the specification of a management control rule to its implementation in the fishery.

First, it is possible that some of the conditions assumed for the assessment will change upon implementation of management. For example, the assessment may have assumed a certain aggregate age-specific selectivity in recommending the management, but during the process of allocation of total allowable catches the resulting selectivity is changed. The assessment will then have to "play catch-up," by incorporating the changed selectivity in the future. The bias in the assessments will be related to the magnitude of the change and the frequency with which assessments are made. It may be possible to assess this bias and to optimize the periodicity of assessments with a simulation model that incorporates the totality of the stock, fishery, data collection, assessment, and management system.

Second, it is possible that certain management controls, such as individual transferable quotas, may compromise the accuracy of the data (e.g. unreported dumping of lower-value products), resulting in bias in future assessments and jeopardizing the effectiveness of the current management strategy. Implementation uncertainty should be considered in the development and evaluation of control rules. Enhanced monitoring will be required in these situations in order to maintain the integrity of the assessments (see Section 5). The data requirements for stock assessment may be categorized as those relating to measurement and sampling errors, those related to parameter uncertainties, and those related to model uncertainty.

2.4.2 Data required to quantify and reduce uncertainty

Each of these different sources of uncertainty has implications for research in terms of minimizing the overall uncertainty and for ensuring that the uncertainty associated with stock assessments can be adequately quantified.

Measurement and sampling errors

In situations for which the measurement errors may be significant, estimates of its magnitude and any potential biases should be obtained. Similarly, it is important to be able to model the errors associated with any sampling program.

If only aggregated statistics are available, it is important to evaluate their precision and accuracy (e.g. through sample sizes).

When some aggregation of the data is unavoidable, it is preferable to maintain as fine a scale of resolution as possible. It is always possible to further aggregate the data, but once aggregated, they cannot be disaggregated.

Parameter uncertainties

The main input parameters in stock assessments are biological ones, such as natural mortality rates, weight-length relationships, and age at maturity.

In some situations, there are no data available to actually estimate these parameters for the stock of interest. In these cases, it is important to include a "reasonable" range of values for such parameters and to determine the sensitivity of the assessment results to this uncertainty.

In cases for which these data are not used directly in the stock assessment model, e.g. the likelihood function can be partitioned, the parameter values, e.g., weight-length relationships, can be estimated independently of the stock assessment. In such cases, not only the expected value, but also the statistical distributional properties, must be available for the assessments. In other cases, it may be important to integrate available data and the estimates of the biological parameters, e.g. growth rates, directly into the assessment models. In such cases the raw data may be required. In either case, the assessments should acknowledge the fact that biological parameters can vary over time and space, and data are needed to assess such changes.

Model uncertainty

Model uncertainty is hardest to account for in most assessments. The problem is that there is generally a paucity of information to formulate and distinguish between competing underlying assumptions about the dynamics. Stock assessment models are simplifications that attempt to represent the dominant factors underlying the dynamics of the stock. The complexity that should be introduced in the model will depend upon the complexity of the system and the scale at which model estimates and predictions for management are needed.

With respect to model uncertainty, it is important to carry out research into the dynamic processes affecting the stock that will allow for distinguishing and refinement among competing underlying assumptions. Generally, long series of data are required for such research (e.g. environmental forcing and auto-correlation in recruitment strength), so commitments to long-term monitoring and research programs are required.

2.4.3 Quantification of uncertainty

The main approaches that have been used to quantify uncertainty in fishery stock assessments are sensitivity analyses, Monte Carlo simulation approaches, and Bayesian analyses. There are advantages and limitations to each of these approaches. Regardless of the approach used, the quantification of the overall uncertainty of an estimate conceptually involves a four-step process:

1. For each potential source of error, a set of hypotheses must be developed;

2. For each hypothesis in Step 1, a relative weight or probability must be determined;

3. For all combination of hypotheses in Step 1, the likelihood (fit) of the resulting estimate must be determined;

4. The results from Steps 2 and 3 must be integrated.

Trade-offs will exist between the completeness of the assessment, the magnitude of the problem, the complexity of the task, the required resources, and the judgements on which uncertainties must be considered. Balancing these different trade-offs will be essential in any particular application in order to be able to provide a meaningful and feasible assessment of the uncertainty. In this regard, some elaboration on each of these four steps is provided as Appendix 2.

The implementation of these four steps requires considerable judgement, so it is recommended that the procedures and the bases upon which the decisions are made be fully documented.

There are a variety of approaches involving various degrees of rigor, formality, and complexity that can be used to implement each of these steps. There is a need for additional research on approaches for incorporating the results from both residual and retrospective analyses into the evaluation of overall uncertainty. In general, quantification of uncertainty will ultimately entail complex models and procedures because of the large model, data, and parameter uncertainties associated with fish stock assessments. It is desirable to limit the complexity to the extent possible and to develop approaches that can screen out redundant or

implausible alternatives, with an overall aim to provide a realistic appraisal of the uncertainty.

The judgments of different experts about the appropriate sets of alternative hypotheses and about their relative weights will differ. For this reason, it is important to attempt to harmonize and integrate the different judgements.

A comprehensive approach to the quantification of uncertainty is likely to be extremely computationally intensive. If such a process is to be embraced, it is essential that sufficient resources, scientists, and time be allocated to the task.

This would have substantial implications for how stock assessments are conducted by several RFBs. Scientific assessments are frequently accomplished by bringing together the data and initial assessments at a working scientific meeting. Then, based on the discussions at that meeting, a final set of calculations is generated and reviewed prior to the end of the meeting. With the comprehensive approach to quantify uncertainty, either substantially longer meetings would be required, or the process would have to be broken into a multi-stage process. If the time allotted to complete the process is too long, however, this could introduce the possibility that substantial amounts of new catch and effort data might become available before the process is completed.

2.5 Alternative sources of information

Much of the information required for stock assessment will be generated either directly from the fisheries or by sampling the catches. Fishery-independent surveys and scientific experiments (e.g. tagging), when they are feasible, may also provide information on the dynamics of the stocks, and thus make important contributions to reduction of assessment uncertainty. Other sources of potentially valuable information are discussed below.

2.5.1 Adaptive learning through probing

In the case of data-poor and newly-developing fisheries, an overly cautious management approach may hinder "learning" about the resource. The use of an active adaptive management approach[1] that incorporates "probing" experiments and/or conducting some of the fishing effort in accordance with a survey design may provide a means of increasing the utility of the data collected. If such an approach is used, the following conditions should be met:

1. An operating model is used to design the experiments or surveys to maximize the "learning" value of the data generated;

2. Adequate monitoring regimes are in place to collect the data in a timely fashion;

3. There is rapid assimilation of new information into the operating model, and adaptive management responses occur as learning proceeds;

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[1] Active adaptive management implies that the management strategy is specifically designed to enhance the information available about the resource, and that future management "adapts" to the new information as it becomes available. On the other hand, *passive* adaptive management implies that there is no specific consideration of enhancing information on resource dynamics in the design of the management strategy.

4. In the case of "probing" experiments involving the infusion of high effort over a designated period of time, there is a management capability to subsequently reduce or re-distribute fishing effort as indicated by the results of the experiment;

5. There is industry consultation and cooperation in the design and implementation of the experiments or surveys.

2.5.2 Industry participation

The involvement of industry in the assessment process has proven to be a useful means of obtaining additional information in many situations. Industry participation has been useful in proposing alternative hypotheses regarding various biological processes, assisting in the interpretation of fisheries data, and planning data collection activities. An additional benefit of industry involvement has been a greater acceptance of the assessment results and the management actions that flow from them.

In addition, there are some specific areas in which increased industry involvement in multidisciplinary research would be of considerable value.

Some of these include:

1. The technical aspects of fishing gear operation and the interaction of fishing gear with fish populations, leading to better quantification of fishing effort, catchability, and size selectivity;

2. The evolution of fishing technology over time, leading to a better understanding of changes in fishing power and, hence, effective fishing effort;

3. Fishing strategies of the various fleets and the factors that influence them, leading to better quantitative models of fishing effort dynamics;

4. Innovative fishing technological approaches to by-catch mitigation.

Industry participation and cooperation in studies such as these would be crucial for their success.

3 IMPLICATIONS FOR BIOLOGICAL AND ENVIRONMENTAL RESEARCH

3.1 Introduction

Tunas and billfishes are broadly distributed throughout the world's oceans, and in most cases fisheries are directed at stocks that range over numerous Exclusive Economic Zones (EEZs) and international waters. The international exploitation of tuna stocks by different fishing gears often makes it difficult to monitor the catches and to develop management protocols. In addition, the broad distributions, highly-migratory behaviour, and complex life histories of the tunas and tuna-like fishes make it very difficult to study them. As a result, despite the large catches, our understanding of tunas and tuna-like fishes is far from complete. Certainly, much less is known about the biology, physiology, and ecology of tunas and tuna-like fishes than of most other species of fish of comparable commercial importance.

Although the mechanisms are poorly understood at this stage, there is growing acknowledgement of the fact that abiotic and biotic environmental changes significantly

affect the distributions, and perhaps also the productivity, of tuna stocks. It seems highly probable that observed changes in tuna populations reflect larger-scale changes in the pelagic ecosystem. Thus, it is important to determine the nature and extent of the impact of climate variability on both the pelagic ecosystems and the tuna stocks.

The tuna fisheries affect the target species, of course. In addition, they affect the species that comprise the by-catches and have more complex impacts on the ecosystem as a whole. The Precautionary Approach specifies the need to conserve the by-catch species and the ecosystem. On a species-by-species basis, the assessment of the impacts and the path toward reduction of the impacts is relatively straightforward. However, the approaches to ecosystem study, and then ecosystem management, are inherently difficult due to the complicated nature of the ecosystem per se, and also to the lack of consensus on the objectives of ecosystem management.

3.2 Pending problems and how they might be solved

The biological peculiarities of the tunas and tuna-like species may severely affect stock assessment estimates, and consequently the validity of the traditional reference points, such as population and spawning stock size, recruitment, natural mortality, exploitation rates, etc. Moreover, these may have cascading negative effects that are difficult to handle, as often a minor part of these uncertainties is included in the models. Some of these are outlined here; however the priorities will be specific and driven by the stock assessment requirement (see Section 3).

3.2.1 Catch at age

In general, it is impractical to age adequate samples of tunas or tuna-like fishes directly. For this reason, age-structured assessments are typically based on conversions of length frequencies to age data, which presents various problems. Such conversions are difficult for tropical tunas that are more than about two or three years old because of their extended spawning seasons. Temperate tunas, which have more restricted spawning periods, can be aged to about four or five years with length-frequency data, but their life spans are much longer than that.

The feasibility and efficiency of direct ageing of tunas and tuna like species should be re-evaluated for both temperate and tropical tunas. Particular emphasis should be placed on improved size sampling by sex, improved statistical analysis of size distributions, validation of ageing methods, inter-laboratory calibration, and development of new methods.

3.2.2 Age-specific natural mortality

Natural mortality is probably one of the major uncertainties, as all age-specific models require this information. Because of the present lack of data, many models consider a constant value of natural mortality for fish of all exploited ages, even if it is accepted by most scientists that it should be age-dependent.

Better estimates of age-specific mortality should be obtained.

3.2.3 Variability in biological parameters in accordance with time and density

Most of the biological parameters may vary substantially with time, in accordance with environmental variation and changes in exploitation rates. Some of them, such as growth and age, are density dependent. These should be more systematically studied because of their strong effects on stock assessment.

Estimates of key biological parameters should be revised periodically to monitor their temporal variation.

3.2.4 Stock structure, spatial heterogeneity and mixing rates

Tuna stocks are often distributed across entire ocean basins, and the same stock may be exploited by several different fisheries. The schooling and migratory behaviours of tunas make it difficult to sample them in accordance with rigorous statistical protocols. Most of the available information on relative abundance comes from catch rates for the various fisheries. Movement among areas is a key element of uncertainty in the understanding of the dynamics of tropical tunas.

Research on stock structure should be intensified, and should include development of improved genetic techniques and use of otolith chemistry techniques that have been used successfully for demersal fishes.

Priority should be given to large-scale tagging programs, using various types of tags, to measure the rates of mixing within and among management areas.

Spatially-structured models should be developed and tested.

3.2.5 Genetic diversity

Most stock assessments include the implicit assumption that an overfished resource will revert to its original status, the "virgin stock," if fishing is discontinued. It now appears, however, that severe overfishing can produce irreversible consequences, which may be due to elimination of one or more sub-populations.

The potential changes in genetic diversity of the tunas and tuna-like species due to exploitation should be studied.

3.3 Impacts of environmental variability

As was noted above, tunas and tuna-like species are highly specialized, with a range of adaptations that allow them to respond rapidly to changes in their environment. Unlike demersal or coastal pelagic species, for which the ability to make large-scale migrations in response to environmental changes is limited, tunas and tuna-like species have the capacity to range over broad geographic areas in search of suitable habitat. Their highly-specialized visceral retia allow them to digest food very quickly, thereby ensuring that the maximum energy can be gained in suitable habitats.

It is likely that the productivity and distribution of a tuna stock is determined by the biological productivity of the pelagic ecosystem in which it is living. Climate variability affects productivity through changes of the physical processes in the ocean. Also, special

features, such as hydrographic instabilities (currents or eddies) or biological enhancement due to run-off or atmospheric transport of elements, such as iron, which can limit the growth of phytoplankton, can be affected by the climate variability near large islands or continental masses. Therefore, variations in climate on various spatial and time scales can be expected to have large impacts on the spatial distribution and levels of abundance of tunas and tuna-like species. Identifying the mechanisms that control this environment-related variability is necessary to conduct the best possible evaluation of tuna stocks, to predict their short- and long-term variation, and to rationally manage the resources. Some examples of impacts of climate variability on tuna populations and fisheries are given below for different time scales.

3.3.1 Inter-annual variability

The strongest and best-documented natural inter-annual climate fluctuation is the El Niño-Southern Oscillation (ENSO), which is an irregular low-frequency oscillation between a warm (El Niño) and cold (La Niña) states.

During El Niño events, the warm waters of the western Pacific (warm pool) extends far to the east in the central Pacific. Conversely, during La Niña events the warm pool is confined to the extreme western part of the equatorial Pacific. It has been demonstrated that such changes occurring during ENSO events have large repercussions on the movement and distribution of tunas. In particular, one of the most successful fishing grounds is located in the vicinity of the convergence zone at the eastern edge of the warm pool. This zone of convergence oscillates zonally over several thousands of kilometers in correlation with ENSO. The extension of the warm waters toward the temperate latitudes during El Niño events also appears to affect the migration of the North Pacific albacore, which are more dispersed in this extended habitat. Consequently, the catch rates are lower during such periods.

As a consequence of the eastward displacement of the warm water masses during El Niño events and the decrease in intensity of the upwelling, the thermocline becomes deeper in the central and eastern Pacific and shallower in the western Pacific. Adult yellowfin and bigeye apparently spend much of their time in or near the thermocline, with frequent ascending movements into the upper warmer waters. Given this behaviour, a deepening thermocline will increase the habitat layer, while a shallower thermocline will reduce it. Therefore, it is expected that a deeper thermocline (e.g. during an ENSO event) will decrease the success of purse-seine fishing in the eastern Pacific. Conversely, increases in longline catch rates observed in the eastern Pacific during ENSO events are generally explained by the deepening of the thermocline that would concentrate the fish in the deep layer where longlines are most efficient. However, it is difficult to discriminate from fishing data the changes due to the catchability from those resulting from spatial movements or variability in recruitment.

There is good evidence that ENSO events have an impact on the level of recruitment of the tunas in the Pacific. High (or low) recruitment episodes of South Pacific albacore and yellowfin have been proposed as the consequence of El Niño (or La Niña) events during the spawning seasons. For skipjack also, the fluctuations in the total catches by the purse-seine fleets in the western and central Pacific Ocean show an important interannual variability unrelated to the fishing effort. In particular, it is interesting to note that in the Pacific Ocean the mature phases of the two most powerful El Niño events, those of January 1992 and January 1998, correspond with the two lowest levels of catch for skipjack. Conversely, the situation was reversed during the 1996 and 1998-1999 La Niña events. These preliminary

results suggest some opposite effects between the eastern and western Pacific that could be linked to the same mechanisms (wind stress, primary productivity, and temperature).

3.3.2 Decadal variability

The effects of interdecadal climate forcing on the oceanic ecosystems have been clearly illustrated. One example is the (north) Pacific Decadal Oscillation (PDO). This oscillation is under the influence of the Aleutian Low-Pressure System, the intensification of which leads to stronger westerly winds in the central North Pacific. This climate change results in increased depth of the mixed layer and increased injection of nutrients into the euphotic zone from nutrient-rich deeper waters. The results suggest strong linkages between the atmosphere, oceanic mixing, and productivity across all the trophic levels of the marine ecosystem. Substantial impacts, with a range of variation in abundance of 30 to 50 percent, have been identified through most of the major components of the marine ecosystems–the primary and secondary producers, the forage species, and several levels of predators. Among the predators, it is likely that the North Pacific albacore is affected by the PDO, as suggested by the declining catches in phase with the environmental change.

3.3.3 Long-term changes

Impacts due to long-term variability are obviously difficult to investigate because of the lack of good fishery statistics over long periods of time. Tuna fisheries have existed for several centuries in the Mediterranean Sea and near Japan. Historical data for the Mediterranean trap fishery show long-term fluctuations in the catches of Atlantic bluefin, by a factor 3 to 10, probably related to environmental variability, during the last two centuries.

The study of climate variability at these different time-scales is fundamental for predicting the potential impacts of the global warming on tuna stocks and, more generally, on the pelagic ecosystem. Simulations and scenarios of climate change due to greenhouse warming include increasing temperature, change in the illumination of the surface layer, where photosynthesis takes place, increasing stratification of the upper ocean, and changes in the oceanic circulation, reducing the nutrient input in the euphotic layer. All of these changes would have direct or indirect effects on the pelagic ecosystem , and thus on the stocks of tunas and tuna-like fishes. It is interesting to note that several simulations suggest that the changes in the mean state of the tropical Pacific Ocean would result in climate conditions similar to present-day El Niño conditions. The potential impacts on Pacific fisheries for tunas and tuna-like fishes include extension of present fisheries to higher latitudes, a decrease in productivity, mainly in the eastern Pacific, increasing variability in the catches, changes in the catchability of the different species, and increasing fishing pressure, particularly on bigeye and yellowfin.

3.3.4 Different time scales and similar mechanisms

From the previous review of studies on climate variability, it becomes apparent that the main mechanisms that link the climate variability to the biological changes in the oceanic ecosystem are similar, whatever the time scale. Scientists have synthethized these mechanisms in a conceptual model. Briefly, the primary forcing resulting from climate change is a change in surface wind stress that affects the depth of the surface layer and the horizontal and vertical flow and mixing within it. This leads to changes in primary production that are reflected in the secondary production. The growth and survival of members of the upper trophic levels are affected through effects on their larvae and juveniles, availability of

food (affected both by changes in productivity and spatial distribution due to change of the meso-scale circulation), suitable habitat, and distribution and abundance of predators and competitors. After a regime shift, both top-down and bottom-up effects occur through the trophic ladder. Climatic variation acts essentially through its impact on success of recruitment. It also affects the fisheries through changes in the efficiency of the different gears. For example, purse seining is less efficient when the wind speeds exceed about 20 knots, and El Niño-related deepening of the thermocline in the eastern Pacific may reduce the efficiency of purse seines. It may lead to new fishing strategies, new technology, or transfer to new fishing grounds, e.g., displacement of the purse-seine fleets from Atlantic to the Indian Ocean and from the eastern to the western Pacific.

Research that leads to an understanding of the mechanisms underlying the recruitment of tunas and tuna-like fishes should be conducted.

Objective (empirical) methods for discriminating between changes in abundance, due to changes in recruitment, and changes in catchability and/or spatial distribution should be developed.

3.4 Catches of target and by-catch species by fisheries for tunas and tuna-like fishes

3.4.1 Definitions

Definitions of by-catch, catch, discards, incidental species, landings, releases, and target species are given in Appendix 3.

3.4.2 Available data

From a global perspective, it is clear that despite the very large catches and significant value of fisheries for tunas and tuna-like fishes throughout the world, we have very little quantitative information on the nature and extent of the discards. This leaves open to question and speculation the impacts of these fisheries on populations of by-catch species. FAO has initiated projects on incidental longline catches of sharks and seabirds.

In the reviews following we summarize, for each major gear type, what is known about the by-catches, which include discards by tuna fisheries in various parts of the world. As few fisheries management bodies request that fishermen record records of discards in their logbooks, and when "sensitive" species are concerned it is highly unlikely that such data could be relied on, the data available derive principally from observer programs run by the CCSBT, IATTC, ICCAT, SPC, and national fisheries agencies.

By-and-large, the coverage of these programs has been limited to a small proportion of the fishing operations, over relatively short periods. Thus, the data collected provide an indication of the species composition in one or more of the capture components, but in most fisheries these data are insufficient to provide reliable estimates of the amounts of fish and other animals discarded dead or released alive, or trends in these.

The application of the Precautionary Approach in the absence of these data, particularly in the case where by-catch species have been classified as threatened, can lead to closures of fisheries. To avoid such drastic actions, we believe it is essential to improve the quality and quantity of observer and logbook data being collected, and to provide some objective assessments of the vulnerabilities of the by-catch species to over-exploitation. The level of

observer coverage would have to be determined in accordance with the questions being addressed. For example, it has been calculated that coverage between 10 and 20 percent of trips is required to estimate the discard levels of the main by-catch species in the purse-seine fishery in the eastern Pacific Ocean.

3.4.3 Vulnerability

The tendency, when looking at lists of by-catch species, is to ignore the species that occur infrequently, or in small numbers. For many species, such as albatrosses and turtles, however, their population sizes, life history characteristics, impacts on populations unrelated to the tuna fisheries, and other factors may all combine to indicate that even modest levels of mortality due to tuna fisheries could be of concern.

There are several characteristics that could be used to assess the relative vulnerability of a species, or group of species. These include, but are not restricted to:

- characteristics associated with greater vulnerability
    - life span
    - age at first maturity
    - reproductive life span
    - trophic level
    - population status (difference between carrying capacity and population size)
- characteristics associated with lesser vulnerability
    - litter size or batch fecundity
    - frequency of reproduction
    - difference between age of recruitment and first maturity
    - geographical range of the species in relation to that of the fishery

The challenge would be development of appropriate indices of vulnerability across phyla (e.g. birds, sharks, and teleosts). This could be achieved by applying appropriate weighting to the characteristics, however. Simulation modelling of any vulnerability estimation would be very useful.

3.4.4 Challenge of developing indices of relative abundance for vulnerable species

While we remain largely ignorant about the impacts of tuna fisheries on by-catch species and pelagic ecosystems, it is obvious that these impacts have increased very significantly over the last 50 years as tuna fisheries worldwide have expanded their catches and effort by orders of magnitude.

Given our observations that data on the levels of by-catch species for most tuna fisheries will not allow quantitative assessment of trends in abundance of any species, let

alone those that are vulnerable and/or present only in very small numbers, we are faced with the challenge of developing methods that will allow this assessment to be completed as quickly as possible.

This is a major challenge because, even if the levels of observer coverage were to be significantly increased, the distributions and catch levels of the by-catch species may not reflect their abundance. For example, in the case of purse-seine fisheries, the level and distribution of catch of species is likely to be influenced by the abundance, drift, and distribution of floating objects.

Research cruises could be planned to routinely estimate the abundances of some pelagic species, to develop some kind of baseline. If conducted on the ocean-basin scale of most tuna fisheries, a routine program that would adequately estimate the abundances of by-catch species for which the populations are small and diffuse would be extremely expensive. However, surveys at intervals of, say, 5 to 10 years, could provide valuable information on trends.

The international nature and basin-scale extent of most pelagic ecosystems remains one of the major obstacles to conducting this kind of research. However, the various RFBs and national organizations have given much lower priority to this type of research than to stock assessment. To effectively address such large-scale environmental problems, major changes in the policy and budget for each of these organizations would be required.

3.4.5 Catches of target and by-catch species by major gear types

Longline

The longline fisheries, especially those of the high seas, catch large amounts of tunas, billfishes, other teleosts, especially pomfrets (family Bramidae), escolars (family Gempylidae), and moonfish (family Menidae), and pelagic sharks and rays, including blue (*Prionace glauca*), shortfin mako (*Isurus oxyrinchus*), oceanic whitetip (*Carcharhinus longimanus*), silky (*C. falciformes*), bigeye thresher (*Alopias superciliosus*), and pelagic thresher (*A. pelagicus*) sharks, all of which have some market value, and crocodile sharks (*Pseudocarcharias kamoharai*), velvet dogfish (family Squalidae), and pelagic stingrays (*Pteroplatytrygon violacea*) which have no market value. For various reasons, fishes other than tunas and billfishes may be retained and landed, or they may be released or discarded at sea. In some cases the fins may be removed from sharks and retained, while the rest of the shark is discarded.

Fish that would normally be retained must sometimes be discarded because they are badly damaged by sharks or mammals (e.g. *Orca, Pseudorca*).

In addition to fish, sea turtles, sea birds, especially albatrosses, and marine mammals are sometimes caught on longline gear. Sea turtles are hardy, and can usually be released alive. Albatrosses are caught mostly in temperate waters. Marine mammals are only rarely caught by longline gear.

The CCSBT requires that longliners use *Tori pole streamers* to reduce the catches of sea birds. In addition, experiments have been conducted with setting longlines only at night, use of devices to reduce the sinking time of the hooks, use of blue-stained bait, use of thawed bait etc. Use of artificial bait, variation in soaking time, and/or use of nylon monofilament

leader may be effective for reducing the catches of sharks. Further experiments with hook timers or time-depth recorder may provide additional information that could be used to increase the selectivity of longlines.

Drift gillnet

Many small-scale drift gillnet fisheries for tunas and tuna-like fishes operate in the EEZs of many nations, especially in the Atlantic Ocean, Mediterranean Sea, and Indian Ocean. Little information on the by-catches of most of these fisheries is available.

Purse seine

Purse seines fish for skipjack, yellowfin, and bigeye in tropical areas and for bluefin in temperate waters.

Purse-seine sets could be classified in the following categories:

- Schools associated with dolphins;
- Schools associated with floating objects (either flotsam or FADs);
- Unassociated schools.

The species and sizes of fish caught by purse seines depend more on the types of sets than on the gear itself.

The dolphin fishery is directed at medium to large yellowfin, but incidental mortality of dolphins is a very sensitive issue in this fishery. This fishery provides a good example of how a by-catch problem has been mitigated by modification of the gear (the Medina panel) and techniques ("backing down," etc.). Sharks, and small amounts of various teleosts, are also caught with yellowfin associated with dolphins. Improved fish detection and identification techniques (i.e. long range sonar) could be useful for detecting tuna schools not associated with dolphins.

Sets on floating objects tend to catch smaller tunas and large amounts of by-catch species, including billfishes, sharks, dolphinfish (*Coryphaena* spp.), wahoo (*Acanthocybium solandri*), rainbow runners (*Elagatis bipinnulatus*), many of which are the targets of artisanal or recreational fisheries, and sea turtles.

Sets on unassociated schools catch tunas which are larger than those caught by sets on floating objects, but smaller than those caught by sets on dolphins. The species composition of the catches of by-catch species is similar to that of sets on floating objects, but lesser amounts of by-catch species are caught in sets on unassociated schools.

During the 1990s the proliferation of sets on FADs has changed substantially the fishing strategy of some purse-seine fleets, which has changed the species and size composition of the tuna catches. More than 50 percent of the tuna catches by purse seiners are presently taken on FADs. Large numbers of juvenile yellowfin and bigeye are taken under FADs, and, in some cases, discarded. The world-wide catch of by-catch species associated with FADs is estimated to be about 100,000 tonnes per year. The catch of by-catch species could possibly be reduced by modification of the fishing gear and/or techniques.

The extensive use of FADs could have other effects on the biology of tunas and tuna-like species. For example, the use of FADs might produce changes in the migration patterns, natural mortality, or growth of these species, or it might affect the associated fauna in ways that cannot be predicted.

In general, introduction of new gears and/or development of new fishing techniques that would increase fishing power should be closely monitored.

Experiments with sorting grids to facilitate the escapement of small fish should be conducted.

Attempts should be made to develop echo-sounders or sonars that indicate the species and sizes of the fish before they are caught.

Pole-and-line

The impact of catching small pelagic fish for bait by the pole-and-line vessels is probably negligible in coastal areas due to the large populations of those species, but it could be of some importance at offshore islands. The use of artificial bait would eliminate whatever objections there might be to catching small pelagic fishes for bait, and would allow pole-and-line vessels to fish more in offshore areas than they do now.

The possible impacts on bait populations in the areas where pole-and-line fleets are active should be studied.

Artificial baits for pole-and-line fishing should be developed.

3.4.6 General recommendations on the problem of by-catches in tuna fisheries

There should be collaboration among tuna research and management organizations and others (other international organizations, non-governmental organizations (NGOs), and interested scientists) to estimate the bycatches, assess the stocks, and investigate ways to reduce the by-catches, especially when the negative effects are serious.

Managerial options to reduce the by-catches, such as requirements that all catches be retained, establishment of quotas on by-catches, establishment of upper limits for by-catch to catch ratios, areal and/or seasonal closures, and requirements regarding gear configuration and/or fishing techniques, should be investigated.

3.5 Ecosystems and tuna fisheries: the Precautionary Approach

3.5.1 General considerations on ecosystems

For many years fishery scientists and managers have relied on single-species models for managing fisheries. These models have been useful, but deficiencies are apparent.

Conceptually, the main problems are:

- The models do not take into account the interactions among different species that are targets of different fisheries or are taken incidentally by them;

- The models did not adequately account for impacts of the fisheries on the habitat, or on other species that occupy the habitat.

The problems with the catch data became apparent when observers first accompanied vessels during their fishing operations, and there was an opportunity, for the first time, to estimate the amounts of fish discarded and to incorporate these data into estimations of fishing mortality.

Some highly-visible discards of by-catch species, e.g. dolphins in the tuna purse-seine fishery of the eastern Pacific Ocean, sea turtles in the trawl fisheries for shrimp, sea birds in the longline fisheries for tunas and billfishes, and many species in drift gillnet fisheries, brought the environmental impacts of these fisheries to the attention of the public. Reduction of the discards was not the only thing that was needed, however. It was already obvious to many scientists that the effects of climate variability, the interactions between target and by-catch species, and the ecological impacts of the fishing operations should be incorporated into a unified system of fisheries management. Ecosystem management, or better, ecosystem-based fishery management, became a cliché repeated by all, but it was never fully defined as a desirable goal, and it is operationally unattainable today.

If, as the Precautionary Approach suggests, fisheries management should evolve in such a way as to require increased consideration of by-catch species, including ecologically-related species, and the ecosystem. It seems likely that this process will be gradual, and will be along the following lines:

Step 1: Modification of current single-species management to accommodate the Pre-cautionary Approach;

Step 2. Determination the appropriate ecosystem parameters, in conjunction with the development of ecosystem-based management goals, objectives, and schemes;

Step 3. Implementation of the Precautionary Approach to the ecosystem-based schemes.

In the context of this process we need to discuss the role of research, understanding that this is dependent on the managers' goals.

It seems likely that the general objective of ecosystem management will be to maintain ecosystem structure and function. Some specific goals are likely to be:

- The impacts of the fishery on other species (discards, mortalities caused by the gear (retained or not retained by the gear), fate and significance of discarded biomass, etc.) are accounted for, and are maintained within pre-specified limits.

- The overall capacity of the fishery is determined by the levels of available targets, and maintained within pre-specified limits.

- The harvest strategies for individual species take into account the potential impacts of the fishery, and also the impacts of other significant anthropogenic factors, such as habitat degradation.

- When many components of an ecosystem are being exploited, the harvest strategies for each exploited species are consistent with ecosystem goals.

- Negative impacts on the habitat, such as discards, damage to the bottom and bottom communities, "ghost fishing," and pollution, are routinely assessed and, if needed, subjected to mitigation programs.

In general terms, ecosystem structure and function is maintained by the conservation of all stocks present within acceptable levels of biomass, and the maintenance of the existing dominance structure. Thus, research must be conducted to determine the properties of the ecosystems, such as the proportions by trophic level and guild, size-frequency distributions, and P:B and other ratios that should be monitored.

3.5.2 Pelagic ecosystems and tunas

It must be acknowledged that we have yet to define or measure the critical parameters of pelagic ecosystems, and that we do not know how to do so.

In general, the catches of most of the world's tuna fisheries have been increasing over the last 10 years, and new techniques, such as FAD fishing, have been developed to increase the efficiencies of the vessels.

The world's tuna fisheries currently catch over 4 million tonnes of tunas and tuna-like fishes each year, and the exploitation rates for many of the stocks of these are estimated to be quite high. It is estimated that most tunas and tuna-like fishes have suffered significant decreases in their biomasses during the last 50 years.

Pelagic ecosystems inhabited by tunas and similar species, such as billfishes, can be characterized by their very large size, compared to any other ecosystems exploited by fisheries. The longline fisheries for tunas ands billfishes operate in an area of more than two thirds of the world oceans (about 50 million nautical miles^2), while the surface fisheries for tunas are exploiting a smaller (but still very wide) area of about 20 million nautical miles^2. These fisheries are exploiting the epipelagic layers of the ocean, the first 100 or 200 m for purse seiners and up to about 300 m, or even deeper, for the longline gear. Tunas, billfishes, and some sharks are among the few species that are heavily exploited in offshore pelagic waters. Many other pelagic species, such various other bony fishes, some sharks and rays, crustaceans, mammals, and molluscs) also inhabit these areas, but there are few fisheries directed at them.

The most significant recent change affecting ecosystems occupied by tunas and tuna-like fishes has been the increase in the use of FADs.

Multidisciplinary research should be conducted on FADs in the various oceans.

The principal goals of this research should be to obtain an understanding of the behaviour of the various species and sizes of fish and other animals associated with FADs and the functioning of this small-scale ecosystem to determine whether FADs are altering the movement patterns and biological characteristics, such as growth and natural mortality, of tunas and other species associated with the FADs. This research should be accomplished with at-sea surveys, experiments on FADs, and analyses of detailed data obtained from purse seiners and FAD supply vessels.

Impacts of the removal of tunas and tuna-like fishes

The effects of annual removal of over 4 million tonnes of tunas and tuna-like fishes from pelagic ecosystems are not understood. As these species are generally highly-productive high-level predators, we would expect, on the basis of trophic models, that the effect would be significant. However, empirical data on food-web effects are not available for pelagic systems, and most classical fishery models were not developed to address that subject.

Improved ecosystem models that will make it possible to better understand and predict the impact of removals of tunas and tuna-like fishes on pelagic ecosystems should be developed. In addition it would be useful to compare the structures of pelagic ecosystems in which the exploitation rates of tunas and tuna like species are know to be different.

Impacts of the removal of by-catch species

We do not currently understand the effects of the removal of by-catch species on tunas and tuna-like fishes. These species should be incorporated into the models discussed above. This will not be possible, however, until adequate data on the quantities of by-catches taken are collected. Also, we have little or no information on the relative abundances or biomasses of many components of the pelagic ecosystem.

Research should be carried out to:

- Develop statistically-designed observer programs (or alternative schemes) to quantify the by-catches in each of the fisheries for tunas;

- Identify the factors leading to by-catch mortality, and use the results of this research to devise mitigation programs;

- Study, through a variety of approaches, such as modelling, simulation, and experimentation, the impacts of catches and by-catches on the ecosystem, with the objective of setting reasonable policies to use in the determination of the target levels for the different components of the ecosystem;

- Develop a vulnerability index that will allow objective assessment of the potential impacts of the fisheries on by-catch species;

- Develop monitoring systems to track changes in the communities affected by the fishery, with special reference to by-catch species, and to species receiving subsidies from the fishery (i.e. discards and fish hooked on longlines). The available options include estimation of abundances by periodic fishery-independent surveys or any other accepted methodology and the development of indices of relative abundances to monitor trends.

When there is scientific evidence that suggests that a species is vulnerable or endangered, it is important to understand the impacts of further removal of the species.

Impacts of the discarded biomass on the system

A fraction of the discards is consumed either on the surface or in the upper water layer by species such as dolphins, sharks, and seabirds. There is some indication that some species benefit from these subsidies, and that they expand their populations at the expense of others.

In addition, several species of marine mammals, sharks, etc., have learned to take fish from fishing gear, occasionally getting entangled during the process. The fisheries can provide a competitive advantage to a species that breaks the balance reached through evolution.

The remaining fraction of the discarded biomass (of both target and by-catch species) sinks down the water column and ends up on the bottom in abyssal depths. The amount in question is not large, given the large area where it is dispersed. However, as the dumping may be quite localized, it may have local effects on abyssal communities.

3.5.3 A suggested approach to pelagic ecosystem-fisheries modelling

Responses of tunas and tuna-like fishes to natural and anthropogenic changes

Understanding and ultimately predicting how populations of tunas and tuna-like species and the by-catch species respond to natural and anthropogenic changes is a major challenge for integrating the ecosystem approach into management. Modelling studies should be directed at elucidating the mechanisms linking biological and physical components of marine ecosystems and understanding the responses of the ecosystems, particularly the populations at higher trophic levels which are exploited by various fisheries, to various types of physical forcing and biological interactions. This would require the development of coupled physical-biological interaction models on the scale of ocean basins, and would include zooplankton, micronekton, and higher-level predators that are not exploited. This multi-disciplinary theme is currently being developed mostly by the international Global Ocean Ecosystem Dynamic (GLOBEC).

The linkages among physical conditions, marine food web structures, and ecosystem or population dynamics should be identified.

Networks of collaboration to take advantage of programs involved in ecosystem research should be developed.

Integration of climatic data into the models

Meso-scale hydrographic features in the ocean influence the distribution and survival of plankton and fish larvae. The development of climatically-driven physical oceanography models appears to be a modelling tool particularly well adapted to the dimension of the pelagic ecosystem for identifying advection routes and areas of retention of tuna larvae and juveniles. Such models should be useful for investigating the mechanisms of mortality at the different juvenile stages, so that the factors that lead to low mortality of larvae and juveniles, and thus maximize year-class strength, could be identified.

Biological productivity in the pelagic zone is highly dynamic, characterized by advection of organisms at lower trophic levels and by extensive movements of animals at higher trophic levels, both of which are strongly influenced by climatic variability. As the potential energy of stored biomass is transferred by the trophic level up the food web, the time scale for transfer between levels increases from seasonal to multi-annual scales. Ecosystem models coupling physical and biological interactions may be constructed from combinations of production and age- (size-) structured population models that are appropriate for simulating space and time distributions of successive cohorts of targeted species. A major research challenge of these modelling studies concerns the parameterization of the mechanisms of interaction among the different modelled components.

Single- or multi-species structured population models developed with rigorous statistical estimations relying on fishing and tagging data are useful for estimating the population parameters, such as biomass, mortality, growth, vulnerability to capture, and gear selectivity. Biological studies (growth, reproduction, and diet), physiological experiments, and acoustic tracking and archival tagging make it possible to better define various aspects of the biology of the species, including their habitat and behaviour. Individual-based models (IBMs) are a useful approach for integrating these different types of information and testing and formulating mathematically the behaviours, growth variability, and survival probabilities of individuals of specific species through time, as determined by environmental conditions. These formulations and parameterizations can be then included in structured population models, coupled to spatially-resolved ecosystem models for providing spatial distributions of the population studied which vary with time.

Transport models with appropriate biological components to determine how large- and meso-scale circulation patterns transport and influence the mortalities of larvae and juveniles should be improved and, if possible, automated.

The methods for sampling tuna larvae should be improved, and methods for sampling and identifying tuna eggs should be developed.

3.5.4 Area-time closures as an approach for the management of tuna fisheries and pelagic ecosystems

Although various area-time closures have been used for the management of tuna fisheries in recent years, the impacts of these are not yet fully understood. For example, short-term closures to fishing on floating objects have been implemented in both the Atlantic and eastern Pacific Oceans to reduce the fishing mortality of juvenile tunas.

In other areas of the world, however, permanent closures of areas have been established to protect the resources and the ecosystem. Even though tunas are highly migratory, there are areas that consistently show high concentrations of juveniles, aggregations of spawning individuals, or large by-catches of other species. As fishing effort could be redistributed outside the closed areas, and enforcement of the closures could be relatively easy with either observers or vessel monitoring systems (VMSs), this type of management measure should be considered as a potentially useful option to be added to those already available. It should be noted, however, that in many cases juvenile tunas are exploited in nearshore waters by artisanal fishermen, and it would not be easy to find employment for these fishermen in other fisheries.

Using models and empirical studies, it should be determined whether closure of areas affects the structure and integrity of pelagic ecosystems and the dynamics of target and by-catch species.

Studies that will form the basis for decisions on the selection of areas for closure, i.e. optimal sizes of the areas, periods during which they would be closed, and ecosystems that would be affected should be conducted.

The potential for use of remote-sensing data to predict areas of high concentrations of juvenile tunas and/or by-catches species should be determined.

3.5.5 Impacts of fisheries on ecosystem resiliency–a caveat

Because many fisheries have been operating for decades, or even centuries, their impacts on the ecosystem may have become part of the evolution of those ecosystems. Equilibria prevailing prior to the fishery may not be reached again, even if the fishery, or its impact, is eliminated, as ecosystems do not necessarily go back along the same tracks they used to arrive at the current situation. This potential lack of reversibility in the dynamics of ecosystems may be due to various additive or independent causes, such loss of ecological niche, genetic erosion of individual populations, loss of specific biodiversity in the ecosystem, loss of keystone species, etc. The recovery of a population, or the reversal of ecosystem changes, depends on a series of factors, many of which are not under the control of man. This should not be considered as a justification for inaction, however.

4 IMPLICATIONS FOR DATA COLLECTION AND STATISTICS

The Precautionary Approach creates an atmosphere in which RFBs, States, and participants in the fisheries for tunas and tuna-like fishes have a common interest in reducing uncertainty in fisheries data, and in establishing standards for quality control, methods of verification, confidentiality of proprietary information, transparency in data processing, and timely data sharing and exchange. The RFBs use two approaches to obtain data, acquisition of information directly from participants in fisheries and acquisition of aggregated data from national organizations.

Two articles of the UN Fish Stocks Agreement addressing directly the issues of responsibility of fishing nations in fisheries data and statistics are:

Article 8.4. Only those States that participate in the work of a subregional or regional fisheries management organization or arrangement, or that otherwise cooperate in the application of conservation and management measures established by that organization or arrangement, shall have access to the fishery to which those conservation and management measures apply, and

Article 17.1. A flag State whose vessels fish on the high seas shall take the necessary measures to ensure that vessels flying its flag comply with subregional and regional conservation and management measures.

All logbook, landings, processing, trade, and sales data should be verified, which is not an easy task. For example, even with the best of data systems, errors are made in data entry. They are often easily identified, and they can be verified and corrected if cost and time are not critical. However, misreporting, non-reporting, and intentional falsification of data are much more serious problems, and not so easily identified, validated, and corrected. They require that the data manager have a comprehensive knowledge of the fisheries, of monitoring and sampling techniques for fisheries, and of data base management, and an understanding of the principles and means by which cross checking and validation of data from different sources may be accomplished.

4.1 Data confidentiality

The RFBs must maintain the confidentiality of information for individual business enterprises. Information obtained from participants in the fisheries is intellectual capital, and, as with property of any individual, when in the hands of others it must be guarded against

loss or devaluation resulting from the manner in which it is handled. The level at which confidentiality of information can be ensured determines in large part the ease with which information is obtained, its level of detail, and its accuracy. The RFBs must recognize that information remains the property of its source, and must not be released in formats or manners that compromise its value to the individuals from which it was obtained. The ability of the RFBs to achieve these levels of confidentiality is ensured through commission resolutions or statements of policy. Further, the nations in which the headquarters of these RFBs are located must not interfere with RFBs' need to maintain the confidentiality of their records. The secretariat of the CCSBT currently does not hold data, but confidentiality of individual data is ensured by the policies and practices of data-sharing by the national program participants.

The RFBs, recognizing that there is a need to provide data to the public in formats that as are as detailed as possible, but which do not compromise confidentiality, have established mechanisms for release of data to the public, including publishing data in various reports, presenting it at meetings, and posting it on their web sites. In many cases the data are aggregated by species, gear, 5-degree areas, and quarters of the year.

A number of mechanisms to protect confidential data have been adopted by the RFBs. These mechanisms provide that those conducting basic research may request access to confidential data by stating the nature of information sought and the purpose for which the information will be used. On consideration of the request, and possible consultation with the sources of the data, access to the information may be provided to the requesting party. Such access is conditional with restrictions placed against subsequent release to others and with a requirement that an account of the results obtained from the use of the data be presented prior to publication or release of the results.

While it is recognized that the detailed data required by the RFBs to meet their objectives and mandates must be available for analysis while being held in confidence, it is also recognized that there must be a transparency in the compilation and sharing of data which leads to mutual trust by the concerned parties that all relevant information are valid and adequate to meet the objectives and mandates of the RFBs. In various instances, nevertheless, the contracting and collaborating parties have denied access of the RFBs to the detailed and/or aggregated data required to meet their objectives and mandates.

4.2 Principal fisheries

4.2.1 Purse-seine fisheries

Purse-seine logbook data provide information on individual sets, including position, times of initiation and completion of the set, type of set, e.g. associated with flotsam or a FAD, associated with marine mammals, or unassociated, use of aircraft, estimated catch by species or size-based species aggregates, wells in which the fish were stored, etc. In general, the species composition of the catch and weights of fish caught recorded in the logbooks are verified by comparison to landings data. While the logbooks may request that the fishermen record information on discards, fishermen generally do not report these data, and they are generally available only from data recorded by observers.

The aggregated data provided to ICCAT and the IOTC are provided by 1-degree latitude by 1-degree longitude by half-month (or month) by the States in which the vessels are registered. There may be delays of up to one year in the provision of these data. The

States often provide data for purse seiners owned by their nationals that are registered in other nations, sometimes without specifying the flag. Because it is the responsibility of the States in which the vessels are registered to provide these data, failure of national organizations to identify catches by vessels operating under different flags may lead to double counting.

The species and size compositions of the landings are estimated by port sampling, although some very limited data on size are collected by observers. In general, port-sampling programs obtain data for all tunas and tuna-like species, although the IATTC regularly samples only yellowfin, skipjack, bigeye, bluefin, and black skipjack, Euthynnus lineatus. It samples billfishes on an ad hoc basis, however. The data on catches and nominal fishing effort from the principal purse-seine fisheries are generally considered reliable. Also, as small tuna are often discarded at sea, this fraction can be sampled only by observers.

Another component of the purse-seine fishery, comprised generally of vessels of limited operational capabilities, can be identified as participating in fisheries for tunas and other species, such as sardines, anchovies, and mackerels. The vessels in this component of the purse-seine fishery are based in many widely-distributed ports, and, though logbook data are available for some of these, others may escape the monitoring efforts of the RFBs, and sometimes the national organizations as well.

4.2.2 Longline fisheries

Longline logbook data, which are generally available only for larger, high-seas longline vessels that use freezer systems for catch preservation, provide information by individual set, including positions at the start and end of the set, and retained catches by species, in weight and/or numbers of fish. They may also include data on species that are discarded at sea. Some logbooks may also include data on gear configuration, construction materials, bait, and species at which the fishery was directed. There may be considerable delays in the submission of logbooks to national authorities, and, except for the southern bluefin tuna fishery, wherein catches are also reported via telecommunications, this may result in delays of up to two years in provision of aggregated data to the RFBs. The data on the catches and nominal fishing effort for some of these longline fisheries are reliable, although delays in availability and, in some situations, deficiencies in coverages of the data are cause for concern.

Data from certain components of the longline fisheries, principally smaller, artisanal-type vessels and fleets that operate from widely-distributed ports and coastal locations are extremely difficult to obtain on a regular basis, and thus may remain essentially unknown. Many small longliners, with their operational capabilities limited by the use of ice or refrigerated seawater (RSW) for preservation of their catches, operate in the Indian and Pacific Oceans. These vessels are based in many widely-scattered ports, many, if not most, of which are not regularly visited by personnel of national organizations or RFBs. In many cases information on the activities of these vessels is not reported to either the nations in which the vessels are registered or the nations in which the owners or operators reside. Fortunately, however, the coastal States are beginning to require that vessels registered under their flags and report their catches to them. In general, estimates of the catch and nominal effort in historical data bases for this segment of the longline fisheries are considered to be underestimates.

Size-frequency data for catches made by larger, high-seas longline fisheries are generally problematic. Measurements are sometimes obtained by the crews of these vessels from small, non-random selections of the fish caught. Fortunately, however, reliable size-frequency data are collected aboard Japanese training vessels. Port-sampling programs are of limited value because these vessels make trips of long duration, and the catches are generally not identified as to individual sets or small area-time strata. Also, the catches are frequently transshipped, which adds further uncertainty to identification of the area-time strata for catches sampled at some stage during the transshipment process. The fish are normally dressed at sea, which, for tunas, usually includes removal of the gills, internal organs, and caudal fins. Dressing of small billfishes includes removal of the heads, as well, and large billfishes are filleted at sea. For sharks, in many cases, only the fins are retained. If weight data are used it is necessary that the condition of the fish at the time of weighing be known and that factors for conversion of dressed weights to undressed weights be available.

Size-frequency data for catches made by segments of the longline fishery with limited operational capabilities (artisanal and ice or RSW vessels) may also be problematic. Fisheries information on area-time strata in which individual fish were captured may be better determined for these, but the wide distribution of the ports in which these vessels are based has generally limited the acquisition of data. As a result, size-frequency data from catches made by this segment of the longline fisheries, with some exceptions, have been generated for ad hoc purposes, and may be limited in scope and coverage.

4.2.3 Pole-and-line and gillnet fisheries

Some of the pole-and-line and gillnet vessels make extended trips. The activities of these vessels are generally well documented by logbook programs, which provide information such as locations, dates, catches by species, types of schools, nominal fishing effort, and bait. The logbook records are generally verified for errors in estimates of weight by comparison to landing data, which in most cases indicate that they are reliable. The catches are often categorized by size rather than species, however, and in such cases port sampling must be conducted to establish species and size compositions. Aggregated pole-and-line data are provided to some RFBs at the level of 1-degree areas and half-months or months by national organizations. In some areas, chartered pole-and-line vessels fish under joint-venture agreements. In most of these joint ventures the catches are reported by the coastal States, rather than by the States in which the vessels are registered. The delays in provision of aggregated data may be as long as one year following the year of catch.

The activities of significant portions of the pole-and-line and gillnet fisheries are not monitored by logbook programs. The trips by vessels in this component of the fisheries are generally are of short duration, frequently lasting only one day. With trips of short duration, information on catch and nominal fishing effort by relatively small geographical area and time can be estimated from detailed landings data when these are available. However, some of the boats that participate in these fisheries are beginning to extend the durations and distances from port of their fishing trips, which will make estimations of the catches and nominal fishing effort by area more problematic. The total catches of this component of the fisheries are frequently estimated by market surveys, which do not record data on fishing effort and locations where fishing takes place. This method provides underestimates of the actual catch. There is thus a general lack of information adequate for stock assessment for these fisheries. Unmonitored fisheries are a particular concern in the Indian Ocean, where they account for nearly half the catch of tunas and tuna-like fishes. In contrast, it is estimated that these fisheries account for less than 5 percent of the catches in the eastern Pacific Ocean.

Size-frequency data from these fisheries is frequently lacking, although some may be obtained by port-sampling programs at selected ports.

4.2.4 Artisanal and recreational fisheries

Smaller-scale fisheries catching tunas and tuna-like fishes include recreational and subsistence fisheries, and commercial troll and harpoon fisheries. Sample surveys and sociological data indicate that these catches are significant. The levels of catch and the information obtained from these fisheries are quite variable, and reliable estimates of the total landings are often lacking. Nearly all fish caught by artisanal fishermen are retained, but large portions of the billfishes caught by recreational fishermen are tagged and released. In general, no effort data or estimates of fishing power are available for either artisanal or recreation gear.

4.3 Other data

It should also be noted that biological and population parameters are subject to change over time, and, while lacking recent information may necessitate the use of data from past studies, analyses and studies of these parameters should be validated by periodic review and updating of the studies to develop recent information.

4.3.1 Biological data

Data on the biology of tunas and tuna-like fishes, and of species associated with and/or captured in fisheries which harvest tunas, are developed from *ad hoc* studies conducted by the RFBs, and national organizations. In general, the objectives of these experiments have been well considered, the experimental designs have been good, and the data obtained have been of good quality. These studies have included research on morphology, physiology, behaviour, feeding, reproduction, age and growth, mortality, movements, and stock structure.

Tagging has been conducted by most of the RFBs and some of the national organizations. Fairly extensive conventional tagging programs have been conducted for the major species of tunas in the Atlantic and Pacific Oceans, but there have been no large-scale conventional tagging programs in the Indian Ocean except for those on southern bluefin. The release data for conventional tagging studies are generally considered very good, but some of the recapture data may be unreliable. Fortunately, however, it usually fairly easy to tell which data are reliable and which are not, and the unreliable data can be excluded in the analyses of the data. Data from experiments with conventional tags yield information on movements, stock structure, growth, mortality, and schooling behaviour. Data from sonic tags yield information on physiology and behaviour, and data from archival and pop-up tags yield information on physiology, behaviour, movements, and stock structure.

4.3.2 Environmental data

Environmental data are generally not obtained directly by the RFBs except in conjunction with *ad hoc* research. A principal exception is observations of hydrographic conditions obtained from logbooks and/or coordinated programs to obtain expendable bathythermograph data from fishing vessels. Applications of results from fisheries oceanography and research that utilize hydrographic and environmental data obtained from research programs, in many cases unrelated to fisheries science, are playing an ever-increasing role in meeting the objectives and mandates of the RFBs.

4.3.3 Observer program data

Observer programs, conducted by RFBs and national organizations, have developed over the last two to three decades. In general, these observer programs were created to monitor activities such as compliance with licensing agreements and restrictions on incidental catches. In addition to providing information required for meeting those objectives, observer programs provide the highest quality and most detailed data on catches and fishing effort, and may also provide environmental data. They also provide essentially the only reliable, detailed information on catches discarded at sea. The coverage of these programs varies greatly from fishery to fishery, however.

4.3.4 Fleet data

Vessel characteristics and operations

The fishing industry continually seeks increased efficiency, incorporating developments in materials, technology, vessel and equipment design, fishing and fish-handling techniques, and fish transport. Most of the RFBs do not compile detailed information on the characteristics of individual vessels, such as fish-carrying capacity or speed, or of their gear, such as net dimensions, use of aircraft, or electronic equipment. Likewise, they do no often compile information on the relative skills of individual vessel captains. In some cases national organizations have limited information on vessels and their gear, but these are not generally supplied to the RFBs, which most frequently have only listings of the vessels and their main characteristics.

Vessel-monitoring and global-positioning systems

Vessel-monitoring systems (VMSs) are increasingly being employed to provide information with which to track the positions of fishing vessels. Most frequently vessels are required to carry VMS equipment as a condition for obtaining fishing permits for territorial waters. The nations in which vessels are registered can impose VMS reporting on vessels operating under its jurisdiction in international waters. A VMS provides a powerful mechanism for positive identification of vessels, fishing grounds, and fishing activity on a current basis. In the absence of VMSs, low-cost global-positioning system (GPS) receivers placed on board a vessel can record its positions at frequent intervals. When the vessel returns to port the records can be examined; the intervals between successive positions provide indications of when the boat had been traveling from one location to another and when it had been moving slowly in a "fishing mode."

4.4 Key problems in improving data quality and coverage

4.4.1 Data aggregation and sharing

In general, aggregated data are submitted to the RFBs by the national organizations, the exceptions being data obtained directly from the fisheries by the IATTC and the SPC. Current arrangements for provision are such that catch and effort data for longline fisheries are provided at the level of 5-degree areas by quarters or months, and data for the surface fisheries data are provided by 1-degree areas by months or half-months. Aggregated data at these levels are quite useful for some research, but data at finer scales are required for some purposes, such as standardization of effort, studies of the effects of local environment on effort or expected species composition in sets, and analyses of catches and effort on FADs. If

the fisheries from which imprecise data are collected contribute relatively minor amounts of catch to the total, the problem is less serious than if it comprises a major portion of the total catches. A key point to note is that the lack of data and/or access to data at fine scales may significantly hamper the ability of the RFBs to reduce uncertainty in their findings.

Detailed data that exist should be made available to the RFBs. The status of data provision by parties should be reviewed by each RFB, and, when necessary, action should be taken to ensure that these data are provided in a timely manner.

4.4.2 Catch and landings data

Illegal, unregulated, and unreported (IUU) catches

Information on catches and landings collected by national organizations may be used for determining tax liabilities, as well as stock assessment, so the vessel owners and captains may falsify their records to reduce their taxes. Logbook records might be used as proof that a vessel was fishing in a closed area. This is not a problem when the data are collected by the RFBs, provided that they are not obliged to show the data to the national authorities.

Large-scale fisheries

The existence of IUU catches by vessels fishing for tunas and tuna-like fishes is well known. Few data are available on these catches and the associated fishing effort. It is believed that these catches are made principally by large, high-seas longline vessels, although such activities by purse-seine vessels have recently become a concern. Although the total number of vessels making IUU catches, and the details of their operations, are not known, some of these have been tracked moving from one ocean to another. It is important to not confuse vessels operating under flags of convenience with vessels making IUU catches, as IUU catches may be made by any vessel at any time. It is considered that the impacts of IUU catches are significant.

ICCAT has adopted trade measures against bluefin tuna and swordfish caught illegally. It identified over 300 longline vessels making IUU catches, and this appears to have had a strong impact on the operations of these vessels. Recently some of the other RFBs have begun collecting information on the activities and operations of vessels making IUU catches, and they are now estimating IUU catches from port-sampling data and trade and transshipment records. For example, ICCAT adopted the bluefin statistical document program, requiring that all bluefin imported into the territories of its Contracting Parties be accompanied with documents indicating the registries of the vessels which caught the fish and the areas and time periods of capture. The information in the documents must be validated by government officials. This system revealed significant amounts of catches which had previously not been reported. Trade data are also used to estimate the IUU catches of swordfish, bigeye, and yellowfin. The port-sampling data also include information on the size compositions of the IUU catches. The CCSBT has implemented a trade information scheme, similar to the ICCAT system, to document the catches of southern bluefin tuna.

The most direct solution for reducing the uncertainties created by IUU catches is to reduce the activities of vessels making these catches, as ICCAT has done. FAO is presently in the process of developing an International Plan of Action for reducing IUU fishing activities. Those combined efforts should be maintained, and similar programs should be put into place by all the RFBs to reduce what is one of the largest, if not the largest, source of error in data collection. Recognizing that the following will require legislative and/or administrative action by individual States, consideration should be given to requiring that then States close ports to vessels identified as having made IUU catches.

Small-scale fisheries

The fisheries of some developing countries are not covered by logbook reporting. In some cases the fishermen are illiterate, the boats too open to the elements to permit paperwork, and/or the boats are too numerous to permit collection and processing of logbooks. Several approaches, including stratified sampling schemes and market surveys, are used to estimate fishery statistics. In large countries, the statistics are usually compiled at the district or provincial level. This, together with manual processing and the fact that fishery statistics are generally not limited to tuna fisheries, imposes considerable levels of aggregation, with much of the detail present in the initial data, such as information on species composition, gear, and effort, being lost.

Samples collected for research purposes should be used to estimate species compositions from aggregated data, recognizing that many assumptions must be made in the process, with concurrent increases in uncertainty.

Most statistical systems used in the past for small-scale fisheries have been unable to cope with data collection for a prolonged period. This has led FAO to develop generic multi-lingual computerized solutions (ARTFISH) intended for sample-survey statistical estimation and reporting. The ARTFISH type of system produces estimates of the catch and effort, and provides estimates of variance in relation to the intensity of sampling chosen, but can collect data on the locations of the catches only through interviews with the fishermen. Data at the initial level are kept throughout the processing and archived, which permits the extraction of data that are of specialized interest. Several national and regional agencies are now collaborating in this development, either through complementary systems, or through training and implementation. These efforts should be continued and expanded where possible.

Other problems with catches

Lack of mechanisms for data collection for non-political reasons

Other important components of catch data that may not be reported to the RFBs result from the lack of mechanisms for data collection or from the data not being compiled at sufficient levels of detail.

The lack of data or the failure of national organizations to compile the data in sufficient detail is a serious problem, and the RFBs generally have to make estimates of the magnitude of these unreported or insufficiently-reported catches. These instances are generally associated with developing countries, and include the catches made by artisanal fisheries, for which the amount of unreported catch can be very significant, as is the case in the Indian Ocean. The recreational catches of billfishes, for which complete data are seldom available,

may be significant for at least some species. The Code of Conduct for Responsible Fishing states that the nations have an obligation to monitor the fisheries and that, if necessary, assistance should be provided to them for developing the required statistical systems. Sometimes very basic data (e.g. logbook, cannery records, and sales records) which would allow such estimation, exist. In some cases trade data may also prove useful in developing estimates of these unreported catches.

It is strongly recommended that the sources for estimating these catches be identified and that estimates be developed by the RFBs and national organizations. The data collection programs should identify and/or develop sources for, and maintain data for, artisanal, recreational, and subsistence fisheries harvesting tunas and tuna-like fishes.

It is likely that at least some historical data exist within industry records, and that with effort and good communication among scientists of the RFBs and the national organizations and individuals from industry, these data may be made available and analyzed.

It is important that the estimates that are developed be well documented, and that they include information on reliability and variability. In addition, the RFBs should assist in establishing, operating, and coordinating monitoring systems for these fisheries and training scientists and technicians for this work. In instances where legislation obligating reporting of fisheries data to the nations in which the vessels are registered and/or the RFBs does not exist, the RFBs should recommend to the States that they adopt such legislation.

Lack of mechanisms for data collection for political reasons

The lack of mechanisms for data collection may be due to political issues. When this arises due to questions about the status of participants, the data are frequently available, but may not be included in the assessments at the international level due to difficulties in participation of representatives for these fisheries. It may be very difficult to solve the problem of RFBs not having access to fisheries data as a result of political problems.

If no political solutions are offered, a solution at the informal and scientific level must be sought. If this fails, assessments and statements of risk must be based on the estimates of missing data developed by RFBs. To the greatest extent possible these estimates should be based on trade statistics, and national agencies, e.g. customs, particularly those of parties to RFBs, should cooperate closely in these efforts.

Landings (retained captures)

Fish discarded at sea

Stock assessment requires data on the total removal of fish from a stock (retained catch plus fish released alive or discarded dead). In most instances, however, the so-called catch data are actually the retained catches. Attempts have been made to estimate discards from logbook records, which occasionally mention discards, but estimates based on logbook records are not good enough to be included in stock assessments. More recently, improved data required for estimates of releases and discards have been obtained from data collected by observers, and it has been demonstrated that the nature of the discards, such as species, size, and condition, varies significantly with area, season, gear type, etc.

Observer programs should be instituted and/or coverage increased, when necessary, to achieve the required accuracy and precision in the estimates of the total catches, the landings, and the releases and discards by category, as required to reduce the risks to acceptable levels under the Precautionary Approach.

Data on releases and discards that have not been processed or provided to RFBs may exist.

Records from observer programs should be checked for data of this nature, and, if found, the information should be included in future analyses.

Conversion to round weights

Landings are frequently not reported as round weight, and this requires that conversion factors be used to convert the weights provided to round weights. Frequently there is lack of information or misunderstanding as to the nature of the weight provided, and sometimes the conversion factors are crude or incorrect. This causes bias and/or significant imprecision. This problem becomes even more serious when trade data are used for landing estimates. In many cases the conditions of products are not known, and the relationships between the trade weights and the round weights have not been documented outside of industry. This problem is further complicated when individual companies view their raw product utilization rates as confidential data critical to market competition. Furthermore, many persons involved in processing and compiling statistics from fisheries are not aware that these problems exist.

The training and education of samplers and statisticians is essential. A bibliography of existing conversion factors should be developed, and copies of the referenced papers, manuals, and/or articles should be maintained in an archive from which copies are made readily available to the RFBs and national programs. A technical manual detailing the common terms and factors required to correctly determine factors required for conversions, and the various conversion factors for tunas and tuna-like fishes, should be developed.

Fortunately, a conversion factor calculated for a species in a particular area is likely to be usable in another area. Nevertheless, the applicability of conversion factors across large area-time strata should be determined, and when the factors are not sufficiently accurate and precise, additional studies should be undertaken.

The continuing applicability of conversion factors should be determined with small-scale validation studies on a regular basis.

Common expressions for processed conditions must be clearly defined, since an expression may have different meanings among companies, regions, and/or fisheries. Dressed weight, for example, can mean gilled and gutted, or it can mean gilled, gutted, and beheaded.

Catches in numbers or weights

Catches are usually reported as weights, but sometimes, especially in the longline fisheries, they are reported only as numbers of fish. For most analyses the catch in weight is required for stock assessment, but in some cases catches in numbers of fish should be used. In either case there is a need for factors for conversion between individual fish size and weight. These are based on the size compositions of the catches and weight-length or length-weight relationships. The size compositions of the catches will almost certainly vary considerably

from area to area and year to year, and the weight-length and length-weight relationships may also vary, perhaps in response to long-term shifts in the environment, which might be introduced by shifts in climate regime. Lack of accuracy in these conversion factors may result in significant errors in the estimated catches, independent of errors that may be introduced by failure to obtain representative size-frequency data (discussed further in a later section).

Biological studies on weight-length and length-weight relationships that include terms for areas and seasons should be conducted. Existing studies may prove valuable in establishing criteria for experimental design. Validation studies should be made on a regular basis.

Misidentified and unclassified species

As previously noted, in industrialized tropical surface fisheries the catches and/or landings of juvenile skipjack, yellowfin, and/or bigeye are usually reported as "skipjack" or "tunas," as the prices of the fish do not differ among species. Juvenile yellowfin and bigeye are quite similar in appearance, so untrained people, even if they want to, cannot distinguish between the two species. At larger sizes, when the prices paid for yellowfin and bigeye are the same, there is a tendency to report both species as yellowfin. When the prices for the two species are different, in some instances, the lower-priced species is over-reported and the higher-priced one is under-reported. Furthermore, if there are regulations that restrict the catches of one species, but not the other, fish of the first species may be reported as the second species. For many years, scientists have been working to correctly determine and report the catches of small fishes by species. In the eastern Atlantic substantial port-sampling programs for catches landed by purse seiners and pole-and-line vessels have been implemented to accomplish this objective. This problem has more recently been recognized in other areas, and corrective measures, including redesigned and more intensive port-sampling programs, have been implemented.

Identification guides that include species recognition of fish of all sizes and both whole and dressed fish should be produced, and observers and port samplers should be well trained in species identification.

Scientists who analyze the data, especially historical data, should be mindful of the problem of species misidentification. When potential bias has been identified, consideration should be given to revising the data to adjust for species misidentification. Because sampling for species composition is labor-intensive and costly, the sampling strategies and experimental designs should be reviewed to determine how to get the required accuracy and precision at the minimum cost. For the areas where sampling for species composition is not being conducted, the catch of juvenile tropical tunas should be carefully documented, and, if problems similar to those discussed are found to exist, corrective measures should be introduced immediately.

Port sampling must also be sufficient to validate species estimates provided by observer programs and to provide checks against falsification of catch reports.

Double reporting

With the introduction of regulations to fisheries harvesting tunas and tuna-like fishes, joint-venture operations have become more common. Most of these operations are charter vessel arrangements between coastal states and vessels from other regions. Under agreements for data reporting developed through the Coordinating Working Party (CWP), the responsibility for reporting of catches and fishing effort rests with the nations in which the vessels are registered. Under certain conditions, however, exceptions to this responsibility are made. Unfortunately, in many instances it is unclear whether a joint venture qualifies for exemption, and the catches are not reported by either nation, or they are reported by both. This problem is likely to become more serious in the near future.

The definitions of responsibility of reporting agreed upon at the CWP should be taken into account. When there is any doubt, the RFB should decide where the responsibility resides.

4.4.3 Effort data

Effort data present even more problems than do catch data. Nominal effort data are collected for most of the large-scale commercial fisheries, but seldom for artisanal fisheries. The fact that the efficiency of the vessels tends to improve over time complicates the interpretation of the data. In general, the changes occur gradually, but sometimes there are sudden and drastic changes, such as the adoption of deep longlines, which are more effective for catching bigeye, and the use of FADs, which increase the catches of skipjack and bigeye by purse-seiners. The problem is complicated by the fact that most of the fisheries for tunas and tuna-like species are directed at more than one species, the fishermen may change their fishing strategies in accordance with changes in the relative abundance of various species, the prices paid for various species, and/or fishing regulations. Scientists must develop techniques to standardize the effort data to compensate for both gradual and sudden changes in fishing efficiency, which requires considerable knowledge of the fisheries and the effect of the environment on the behaviour of the fish, and sophisticated analyses of large amounts of data.

Collection of data on nominal fishing effort should include collection of ancillary data for factors which are known or suspected to have impacts on effective fishing effort, including directly questioning or requesting in logbooks that the targets of fishing effort be clearly identified. Logbooks should also request information on the gear configuration on each set of the gear (for longlines), and for the trip (for other gear types). The RFBs and national organizations should develop and maintain data bases on vessel specifications and gear configurations and operations, preferably on a trip-by-trip basis. If aggregated data are provided to the RFBs by the national organizations, the data provided and the levels of stratification should include detailed gear configuration and targeting data, including the number of FADs involved in the operation and the characteristics of the data provided by the FADs, i.e. location only or information on fish presence and/or oceanographic conditions.

A non-exhaustive list of the kinds of data which should be obtained in association with nominal fishing effort data includes gear specifications, gear construction materials, other auxiliary equipment and gears used, school type, times and positions for starting and ending fishing operations, bait used, use of supply vessels, including transfer dates and amounts, use of oceanographic data obtained directly from satellite or from companies providing current oceanographic and/or weather data, use of aircraft, and use of FADs.

Contribution to the understanding of the efficiency of effort may be gained from discussions with representatives of the fishing industry, but it should be considered that information received may be confidential, due to the perception of those implementing new technologies that the technology gives them a competitive edge. Nevertheless, it is vital that information on developing technologies and vessel characteristics be maintained. The experience and skill of the captain or fishing master is a significant factor in understanding the performance of fishing vessels and effective fishing effort.

The logbook data systems should include records of the captain or fishing master for each trip.

4.4.4 Incidental catch data

As the Precautionary Approach is applied in management, restrictive measures may be applied to tuna fisheries that are based not only on the condition of the stocks of tunas and tuna-like fishes, but also on considerations of species inadvertently caught in association with tunas and tuna-like fishes. Some of these, e.g. sharks, dolphinfish, wahoo, and rainbow runners, are important to artisanal fishermen, others, e.g. billfishes, are important to recreational fishermen, and others, e.g. sea turtles, sea birds, and marine mammals, are important to society, in general. Therefore, the studies of these incidental catches, regardless of whether they are retained or discarded, are of utmost importance to the RFBs and to all nations with fisheries for tunas and tuna-like fishes. Except for the data obtained from observer programs, information on the catches of species other than those that are marketable are minimal. However, data on some species and aggregates of species are available in logbooks, particularly those of longliners. Attempts have been made to estimate the catches of selected species (e.g. Pacific and Atlantic blue shark) by using these logbook records in conjunction with data on the species compositions of the catches of research vessels. These estimated catch data are important sources of information for implementation of the Precautionary Approach.

Emphasis should be given to the collection of data on the incidental catches of fisheries for tunas and tuna-like fishes.

Some RFBs (e.g. ICCAT) require that the Contracting Parties report the incidentalcatches, and some have developed reporting forms for incidental catches (retained and discarded) and are adjusting the data as described above. Logbook and observer programs should be modified, if necessary, to require the reporting of all catches, regardless of category or species. Historical data from logbook and observer programs should be examined for opportunities to estimate the catches of particular species directly or with the use of ancillary information.

4.4.5 Vessel-monitoring and global-positioning systems

Vessel-monitoring systems (VMSs) and global-positioning systems (GPSs) have been discussed in Section 5.3.4.2.

The RFBs should develop requirements that each vessel operating in fisheries which may capture tunas and/or tuna-like fishes carry a VMS or keep records of positions obtained from an onboard GPS, and that the data from this system be available to the RFBs.

4.4.6 Biological data

Tagging

A well-designed and -executed tagging program can be of benefit in undertaking resource assessments. Execution must include placement of the tags on the fish, collection of the tags and corresponding recapture data, maintenance of the tagging data base, and analysis of the data. A poorly-designed or -executed program, however, is likely to be of little or no value, and may even complicate or compromise concurrent well-designed and -executed programs.

The RFBs and national organizations should actively encourage the implementation of well-designed tagging programs and, when appropriate, seek to improve existing programs.

Size frequencies

For stock evaluation and other biological studies of tunas and tuna-like fishes adequate size-frequency data are essential, because the principal means for estimating the age of individual fishes in the catch are based on measures of size. These age-at-size data are generally validated with studies of hard parts or tagging data, but for some species validation has not yet been accomplished. The port-sampling programs of the RFBs and the national organizations obtaining data from the catches of large purse-seine vessels provides a high level of coverage in terms of areas and times of the catches, even when stratified sampling designs are not used. The reasons for this include the ease of access to the catches during unloading or in the processing facilities and the relative accuracy with which the areas and time periods in which the catches were made can be identified, even when the vessels are in port. In general, the sampling of the catches of longliners is less satisfactory. The reasons for this include the facts that the vessels operate far from their home ports, the trips last for very extended periods, most of the catches are transferred from fishing vessels to freezer vessels before they are landed, and the fish are dressed at sea. Until recently the sampling of the catches of longline vessels has been conducted by the fishermen, which has resulted in low coverage rates and inaccurate measurements, particularly for species that are less abundant in the catches, but which are often the most important from the standpoint of assessment and management. Also, although fishermen are instructed to sample randomly, it is suspected that this has often not been the case. An exception is the Japanese program for southern bluefin, for which every fish is measured. Low coverage and sampling rates result in inaccurate raising factors being used to make estimates of the catches at size. Also, no samples, or inadequate samples, are obtained for some area-time strata, in which cases size-frequency data for other area-time strata are used to approximate the size distributions of the catches in strata for which there are few or no data, which may add significant uncertainty to the analyses. These are serious problems, since often the size-frequency data that are available represent only one in more than 1,000 fish caught in an area-time stratum. Also, for various reasons, data for catches made by artisanal fisheries are scarce. This can be relatively easily solved in some cases by developing and implementing well-designed sampling programs at the major ports where the fish are unloaded. Fortunately, determination of the area-time strata in which the fish were caught is not a problem with artisanal fisheries.

Well-designed, stratified sampling programs for longline catches should be developed and implemented.

It is believed that observer programs, much increased from present levels, would provide these invaluable, required improvements in data quality and quantity. In cases for which observer data are not available, port sampling is the only data source. It is not clear that port sampling alone would provide the required information, due to the difficulties of validated identification of catches to specific area-time strata. The port-sampling programs of ICCAT have provided cross-validation checks and information that identified major errors in national data collection programs. Thus it is considered that port-sampling programs should be designed to cross check and validate data collected by observers. It is expected that technological developments will lead to improvements in collection of size-frequency data in port and at sea. Obtaining size-frequency data from camera records obtained at sea during fishing operations may provide significant improvements in data quality and quantity. Measurements using infrared or laser technologies may also be developed and routinely adopted. Research on new technologies that appear promising for increasing the quantity and quality of size-frequency data should be conducted. Studies on age determination should also be conducted to obtain and/or validate the age-size relationships used in stock assessments.

Sex ratios

Information on the sex ratios of the catches must be collected for species for which sexual dimorphism is known to exist. Obtaining information on sex ratios is presently possible only by examining individual, whole (ungutted) fish, which is difficult to do. Most of the longline-caught fish are dressed at sea, so it is not possible to examine their gonads. Also, at some landing ports and stations industry personnel do not allow samplers to cut the fish open to examine their gonads. Problems caused by inadequate sample sizes and data substitution for missing information in size-frequency data apply as well to these data.

Studies of the distribution of sex ratios and reproductive activity on appropriate area-time scales should be conducted, and gonad indices should be validated for individual species of billfishes. Data required to estimate sex-specific catch at size should be collected at sea by observers and in port by samplers.

4.4.7 Environmental data

As noted previously, environmental data collected for purposes unrelated to fisheries science are playing an ever-increasing role in meeting the objectives and mandates of the RFBs. There is a great concern that the sources of data that have proven most useful in these respects may suddenly become unavailable or unreliable as the programs generating the data are modified or completed.

The sources of hydrographic and environmental data that are identified for use in research and applications by the RFBs and national programs should be cataloged, and the providers should be informed of the uses to which the data are put and of their value in meeting the mandates of the RFBs and the Precautionary Approach. The RFBs and national organizations should coordinate efforts to keep useful environmental data series available and current.

4.4.8 Fleet data

As noted previously, detailed data on the characteristics of individual fishing vessels and their gear are not usually collected by the RFBs or national organizations. Such data are necessary for standardizing fishing effort, and if this is not done increases in vessel efficiency

may cause the fishing effort to be under-estimated which could, in turn, cause serious mistakes in stock assessment.

The RFBs and national organizations should collect detailed information on the vessels participating in fisheries that capture tunas and tuna-like fishes and on their equipment.

These data collection programs should to be designed in consultation with scientists, engineers, and fishery technicians. The data should be considered highly confidential. Data collected by national organizations should be made available to the RFBs. Periodic reviews of these data should be conducted to determine whether changes in the vessels, gear, and/or techniques employed are affecting the scientific analyses.

5 CONCLUSIONS

The application of a Precautionary Approach establishes a framework in which fishery managers, scientists, and users of the resource contribute in different ways to the achievement of specific management goals. While fisheries managers have the primary responsibility in the definition of a management strategy, there are clear implications regarding the role of scientific research in this process. The implicit obligations of scientists are to determine the status of stocks relative to limits and targets, to predict the outcomes of management actions for reaching the targets and avoiding the limits, and to characterize the uncertainty in both of these.

Scientists should assist in the evaluation of potential management strategies. Data collection, biological research, and stock assessment are integral parts of fishery management strategies. The links between these should be explicitly incorporated into the evaluation of alternative management strategies. It is also incumbent on the scientists to assist managers in prioritizing the research investment to reduce existing uncertainties. Once implemented, management strategies should be regularly re-evaluated to assess their effectiveness in achieving management goals and to determine whether they portray accurately the risks associated with management actions.

Communication between scientists, managers, and users of the resource is an important component in the Precautionary Approach. While the exact form of that communication will depend on circumstances, the principles of transparency, information content, and simplicity should be considered when developing communication channels.

The appropriate characterization of uncertainty, in terms of both precision and accuracy, is one of the main research implications of the Precautionary Approach. There are potentially large uncertainties in the inputs to assessment models and in the results of those models. It is essential that those uncertainties are taken into account in stock assessment by incorporating realistic levels of model complexity and/or consideration of alternative hypotheses. This is a complex task and there is a need for continuous research to improve and develop the mathematical techniques for doing this.

In addition to quantifying these uncertainties, scientists and managers should develop strategies to reduce uncertainty in stock assessments through appropriate data collection and research. Although the details of these strategies will depend on the stock under consideration, there are areas of important research for most of the stocks of tunas and tuna like fishes.

For several those stocks information on key biological parameters is lacking. The impact of this is to increase the uncertainty of the stock assessments. Increased research effort is necessary in several areas, such as validation of age and growth, determination of stock structure, estimation of mixing rates, estimation of the effects of climate on the movements and recruitment of tunas and tuna-like fishes, and description of their habitats.

Active, multidisciplinary, well-coordinated research on FADs is necessary to investigate the impacts of FADs on the movements and behaviour of the tunas and other species that are attracted to the FADs. In addition, it is necessary to better understand the influence of FADs on pelagic ecosystem structure and dynamics. This research should be conducted with at-sea surveys, experiments using instrumented or common FADs, and detailed data obtained from purse seiners and FAD supply vessels.

Improved and routine assessment of the movement patterns of tunas is required. In particular, research is needed to determine how these relate to environmental variability (diffusive and advective, vertical, and horizontal movements). This recommendation applies to most stocks of tunas and tuna-like fishes worldwide. Large-scale, scientifically-designed tagging programs remain the basic tool to obtain a wide range of critical biological information.

Application of the Precautionary Approach also implies consideration of the ecosystem. Both the U.N. Fish Stocks Agreement and the FAO Code of Conduct refer to the need to conserve aquatic ecosystems. However, the notion of conserving aquatic ecosystems is poorly, if at all, defined. More effort should be devoted to express this management goal in an operational way.

Scientists can assist in defining operational objectives for ecosystem management. Empirical studies are needed to: (1) to describe the structure of pelagic ecosystems, (2) delineate the boundaries of pelagic ecosystems, and (3) to determine the trophic dynamics of a range of ecosystems. Using the results of those studies, ecosystem indices should be identified and estimated and ecosystem models improved. International multidisciplinary cooperation among scientists interested in pelagic ecosystems is an essential element in developing this area of research.

Research on new technology and/or novel uses of existing technology can improve our ability to collect data and reduce the impacts of tuna fisheries on the ecosystem. For example, automatic onboard camera systems may be useful to evaluate the species and sizes discarded, and remote sensing data could be used to predict areas of high concentration of associated juveniles and/or by-catch species. Improvement of sonar and/or sounder equipment could lead to a precise identification of size and species before setting. Development of escapement devices for unwanted species, such as escapement grids for small tunas and devices to reduce seabird mortality, could reduce the mortalities of those species.

In the absence of good data, accurate scientific assessments are problematic, and uncertainty is greater. The data available for assessing the fisheries for tunas and tuna-like fishes vary considerably both in quantity and quality. While deficiencies in data programs are recognized and there are ways to improve those data, there are no universal solutions, and management agencies need to carefully determine their research requirements, which, in turn, determine the priorities for data collection.

Not all current data collection programs provide complete and precise sets of data for assessments of stock status. Attempts should be made to increase the coverage and improve the quality of the data and, at the same time, to quantify, to the extent possible, the uncertainties associated with the data.

Deliberate illegal, unregulated, and unreported (IUU) fishing is a major cause of uncertainties in estimating total catches, and reduction of IUU fishing is the solution to this problem. In addition, reluctance or incapacity of national authorities to collect and share available data on IUU fishing with RFBs adds uncertainty in reported total catches, which must be solved at the RFB level.

Other problems in statistics are generally associated with inadequate data coverage and data quality, attributable to lack of good logbook systems and/or sampling systems. For example, the sampling system must be capable of providing data for accurate estimations of the species compositions of the catches. Problem areas, including incomplete records of the catches and biased sampling, and the corresponding solutions, are identified in detail in the section on data collection. In general, increased data coverage and higher quality of the data must be achieved by the national organizations and the RFBs, but also through collaboration among the RFBs, by establishing proper sampling programs, increasing logbook coverage, and increasing observer coverage.

More attention should be paid to designing data collection systems that would reduce the uncertainties associated with effort data.

Estimates of by-catches are presently lacking. To collect these data, well-designed scientific observer programs are required. These programs not only provide data on the amount and composition of the by-catches, but also information that can be useful in identifying factors affecting by-catch, thus leading to identification of possible mitigation measures. Observer programs also provide data for use in tracking changes in fishing efficiency, such as changes in the operations of the fleets or the deployment of new technologies, for which current logbook and sampling information may not provide sufficient information.

There must be recognition by national organizations of the requirements of the RFBs for maintaining confidential data, and the need for a significant improvement in the availability and sharing of existing data among national organizations, including those of non-member States, and RFBs (e.g. catch and effort data at fine temporal and spatial resolutions to compute indices of abundance).

Increased participation by the industry in this process would be of considerable value, for example, in proposing alternative hypotheses regarding various biological processes, assisting in the interpretation of fisheries data, planning data collection activities, and developing technological innovations to reduce the by-catches. As the Precautionary Approach allows more precise management as the overall uncertainty decreases, there is an additional incentive for the industry to participate in information-gathering activities.

For the implementation of a Precautionary Approach, it is required only that scientists provide their best scientific assessment of the uncertainties related to the status of the resource. However, all parties involved in the management of a resource should work toward reducing the existing uncertainties to the greatest extent possible in order to minimize risks and increase the benefits to be derived from the resource.

APPENDIX 1
CONCEPTUAL AND PRACTICAL CONSIDERATIONS FOR THE QUANTIFICATION OF OVERALL UNCERTAINTY IN STOCK ASSESSMENTS

The quantification of the overall uncertainty of an estimate conceptually involves a four-step process:

1. For each potential source of error, a set of hypotheses must be developed. (It should be noted that a set of hypotheses does not have to be a group of discrete alternatives, as it can be represented by a continuous distribution.);

2. For each hypothesis in Step 1, a relative weight or probability must be determined;

3. For all combinations of hypotheses in Step 1, the likelihood of the resulting estimate (e.g. the fit of the data) must be determined;

4. The results from Steps 2 and 3 must be integrated to provide an overall assessment of the uncertainty or risk.

Step 1: Develop hypotheses for each source of error

The possible range of alternatives that could be reasonably considered is often very large. A balanced set of hypotheses representing the overall uncertainty must be considered. It is not appropriate to consider only "optimistic" or "pessimistic" alternatives. Consideration must be given to both their relative plausibilities and their relative likely impacts on the results.

In general, relatively implausible hypotheses should not be considered. However, the extent to which "low probability" hypotheses should be included depends in part on the risk criteria that the managers are using, combined with the possible consequences if those hypotheses were satisfied. For example, a decision about whether to consider stock-recruitment functions with depensation will often be a judgement involving these two factors. Similarly, highly-plausible alternatives can be collapsed into a single alternative if they result in similar estimates or consequences. For example, small uncertainties associated with weight and length measurements can generally be ignored.

The problem in using the "relative likely impact" as a criterion for deciding whether to include an alternative hypothesis is that the relative impact cannot often be determined until the calculations in Step 3 are completed. Some preliminary calculations, plus common sense, can assist in this process. In general, when reasons exist to suspect that an alternative hypothesis may have a large effect, it should be included. Nevertheless, considerable judgement is required.

Step 2: Determine a relative weight for each hypothesis

This process requires considerable scientific judgment. In Bayesian approaches, this is referred to as specification of the priors, and is an explicit part of the process. It is often not realized that other approaches for assessing uncertainties, either implicitly or explicitly, involve specification of prior weights for alternative hypotheses. Thus excluding some alternatives is like assigning zero weights to them. Similarly, Monte Carlo simulation methods require specification of the relative probability or weight to be given to each

realization in the simulation through the assignment of probability distributions to the input parameters in the simulation. Even interpretation of sensitivity analyses requires implicit weightings, either by the scientists or those using the results, of the likely probabilities of the different alternatives presented.

The following hierarchy (Sainsbury, K., D. Butterworth, C. Francis, N. Klaer, T. Polachek, A. Punt, and T. Smith, 1995, Incorporating uncertainty into stock projections—Report of the Scientific Meeting 3-7 April 1995, CSIRO Marine Laboratories, Hobart, Tasmania, Australia: 51 pp) is suggested in selecting the range of alternative hypotheses and assigning relative weights:

a) How strong is the evidence for the alternative in the existing information for the species under consideration?

b) How strong is the evidence for the alternative in the existing information for similar species?

c) How strong is the evidence for the alternative in the existing information from any species?

d) How strong is the theoretical basis for the alternative?

Step 3: Determine the likelihoods for all hypotheses

Determining the relative probability (or output weight) of a resulting estimate from a model, given the input data for a particular combination of hypotheses, also requires scientific judgement. The most common approach for deciding on the output weights is to construct an overall likelihood function for the parameters of the model, given the data. The results, in some cases, can be sensitive to the specification of these, particularly when there are several data sources.

Difficulties arise when not all of the alternative hypotheses for the model structure use the same data sets. Two alternatives for dealing with this problem are: (1) to further develop the alternative model structures so that they all use the same data or (2) to conduct separate analyses for each model structure and compare the end results. In the long term, the first alternative is preferable, and attempts should be made to have the estimation models incorporate all of the relevant data.

Another aspect of Step 3 is consideration of model mis-specification, which may be guided by examination of the results of a particular realization (i.e. pertaining to a particular combination of alternative hypotheses). Such examinations may involve analyses of the residuals, retrospective analyses, and "reality" checking relative to predictions derived from the model. Analyses of the residuals can be conducted with standard statistical diagnostic tests. However, there are complications in applying standard diagnostic tests to complex estimation models because the procedures for detecting model mis-specification are not well developed for complex models. Most commonly, examination of the residuals is used to provide a zero to one weighting to particular realizations or classes of model. Retrospective analyses can also provide an indication as to whether model mis-specification is occurring. Generally, the results of such analyses have been used in a qualitative sense, e.g. to suggest that caution should be used in the interpretation of the results. There is a need for additional

research on approaches for incorporating the results from both residual and retrospective analyses into the evaluation of overall uncertainty.

Over-parameterization is another complication in Step 3. Problems with lack of fit in residuals can always be solved by increasing the number of estimated parameters. Increased parameterization, however, eventually leads to model over-specification and to inappropriate model predictions. Likelihood-ratio tests, or their Bayesian analogues, can sometimes be used to provide guidance here. There are issues related to plausibility relative to Step 1, however, particularly in relation to the power of such tests to distinguish among competing hypotheses. This issue is particularly important when the model results are used to extrapolate beyond the range of observed values (e.g. the ability to distinguish between linear and non-linear relationships with small amounts of data).

Step 4: Integrate the relative weights and likelihoods

Integrating the results of steps 2 and 3 is straightforward, in principle, although it can be computationally intensive. Conceptually, this step entails multiplying the results of Steps 2 and 3 together to provide a probability distribution across the full set of alternative hypotheses. This probability distribution then provides a quantitative measure of the uncertainty associated with the quantity being estimated. In practice, the full set may be very large (or infinite), and a sampling-estimation procedure is required.

The extent and completeness with which each of these steps can be successfully completed in any given application will depend on the availability of data, on the basic knowledge about the underlying system, and on the availability of scientists and time. When the existing data are not very informative, the resulting probability distribution from this process will reflect primarily the prior distributions assigned in Step 2. In this case, the uncertainty will be simply a reflection of the alternative hypotheses selected and the weights assigned to them in Steps 1 and 2. Unless there is a consensus that the prior information is highly informative, the resulting probability distribution for the quantity of interest will be very broad. Moreover, different experts' judgements about the appropriate sets of alternative hypotheses and about their relative weights will differ. For this reason, it is important to attempt to harmonize and integrate different judgements into a single prior. If this cannot be achieved, quite different results can occur, as they have in some cases. There is no easy or quick solution in such situations. Essentially, the only solution is to collect more data.

APPENDIX 2
GLOSSARY

By-catch	Catch of species other than the intended target species in a fishing operation. By-catch can either be discarded or landed
Catch	Fish caught by fishing operations. Catch can be partitioned into categories, such as target or incidental, landed or discarded, discarded dead or released alive, etc.
Control rule	A way of expressing actions to be taken under a management strategy, depending on the status of the stock
Discards	The portion of the catch that is not retained aboard vessels. Discards can be live or dead
FAD (fish-aggregating device)	An artificial or natural object placed on the surface to attract one or more species, thus increasing their catchability
Fishery controls	Tactics used by managers to regulate fishing activities. Controls can be catch or effort limits, closed areas or seasons, etc.
Incidental species	Species which are caught by fishing activities directed at other species
Landings	The part of the catch that is retained and landed
Limit reference point	A reference point intended as a conservation boundary. According to the UN Fish Stocks Agreement, limit reference points should be used to constrain harvesting at levels within which the stocks can produce maximum sustainable yields
Management strategy	The entire set of actions designed to achieve the goals of management. Broadly, a strategy includes every aspect addressed in this report, plus socio-economic and enforcement issues
Overfished	A term used when the abundance of the stock is "too low," meaning below the limit biomass reference point
Overfishing	A term used when the fishing mortality being exerted on the stock is "too high," meaning above the limit fishing mortality reference point
Reference point	A benchmark against which an estimate about the stock can be measured in order to determine its status and guide fisheries management
Releases	(1) The portion of the catch that is discarded alive at sea or (2) in tagging studies, the fish that are tagged and released at sea

RFB	regional fisheries body
Risk	The probability of something bad, such as exceeding the limit reference point as a result of taking a given level of catch from the stock, happening
Status	A determination made, on the basis of stock assessment results, about the condition of the stock and of the fishery. Status determinations are often made with respect to reference points. See Overfished and Overfishing
Target reference point	A reference point intended to meet management objectives (such as maximization and stability of the catch and socio-economic considerations)
Target species	The primary species for which the fishing activities are conducted
Uncertainty	The incompleteness of knowledge about the state or processes of nature

APPENDIX 3
REPORT OF THE EXPERT CONSULTATION ON IMPLICATIONS OF THE PRECAUTIONARY APPROACH FOR TUNA BIOLOGICAL AND TECHNOLOGICAL RESEARCH

Phuket, Thailand, 7-15 March 2000

Opening

1. Mr Charnchai Suntharamat, Governor of Phuket, welcomed the participants in the Consultation. Dr Robin Allen, Director of IATTC and Chairman of the Consultation, thanked the Governor for his welcome, explaining the need for the precautionary approach and its role of in fisheries management. The Consultation was opened by Mr Dhammarong Prakobboon, Director-General of the Fisheries Department of the Royal Government of Thailand, who emphasised the very important role of the tuna canning industry in Thailand and the need for further development of the tuna fisheries of Thailand. In this context, he stressed the need for conservation of tunas and management of tuna fisheries.

Plenary Sessions and Meetings of Working Groups (WG)

2. During the introductory Plenary Session, Dr Allen outlined arrangements for the Consultation. These were established at the meeting, held on March 6, 2000, of the Consultation's Steering Committee (SC) and of the Convenors of the Working Groups (WGs) that were created by the SC to carry out the work preparatory to the Consultation.

3. Dr Jacek Majkowski (FAO), Convenor of the Consultation, introduced its prospectus, mentioning that the Consultation was co-organized by:

- the Commission for the Conservation of Southern Bluefin Tuna (CCSBT),
- the Food and Agriculture Organization (FAO) of the United Nations (UN),
- the Indian Ocean Tuna Commission (IOTC),
- the Inter-American Tropical Tuna Commission (IATTC),
- the International Commission for the Conservation of Atlantic Tunas (ICCAT), and
- the Secretariat for the Pacific Community (SPC),

in collaboration with:

- the Department of Fisheries of the Royal Government of Thailand.

A list of participants in the Consultation is given in the Annex.

4. The proposal for the Consultation originated from a recommendation of the ICCAT Tuna Symposium held in Ponta Delgata, Sao Miguel, Azores, Portugal, in 1996, recognizing the existence of similar research problems with the implementation of the precautionary approach for tuna fisheries on the global scale. The recommendation follows from the adoption of the precautionary approach in:

- the Agreement for the Implementation of the Provisions of the UN Convention on the Law of the Sea of 10 December 1982 Relating to the Conservation and Management of Straddling Fish Stocks and Highly Migratory Fish Stocks and

- the Code of Conduct of Responsible Fisheries,

resulting in a challenge not only to fisheries managers and the industry, but also to researchers. The adoption of the precautionary approach necessities strategic thinking from tuna scientists to identify new requirements for stock assessment, data collection, and basic biological and fisheries technological research. In particular, uncertainties in the knowledge on target, by-catch, and ecologically-related species and on their physical environment (particularly on the impact of fisheries on them) should be quantified. Reductions in these uncertainties may allow the adoption and implementation of safer and more optimal fishing regimes, potentially benefiting the industry and the community at large. The Consultation was limited to biological and technological aspects, which could be readily addressed within the framework of tuna fisheries bodies and international technical programmes.

5. The objective of the Consultation was to prepare a technical document entitled *"Research Implications of Adopting the Precautionary Approach to Management of Tuna Fisheries."* Dr Majkowski acknowledged the effort of the WGs, particularly their Convenors, in collating materials as input for that document before the Consultation and summarizing them in the form of written contributions to the document.

6. The Programme of the Consultation was determined by the Steering Committee (SC), composed of representatives of the co-organizing institutions. The SC established the following Working Groups (WGs):

- WG on Stock Assessment,

- WG on Data Collection and Statistics,

- WG on Biological and Environmental Research, and

- WG on Fisheries Technological Research

to carry out the work preparatory to the Consultation.

7. Also at the first Plenary Session, Dr Allen proposed the outline of the technical document on research implications, seeking feedback from the Convenors of the WGs. That proposal was based on the preparatory work of the WGs. Each Convenor suggested how this outline could be substantiated, using materials already prepared by the WGs and by supplementing them. The Consultation recognised that the resulting document would focus on important aspects of tuna research, but that it should not be regarded as comprehensive.

8. To overcome an overlap of issues raised by the WG on Technological Research with those raised by the other WGs, the SC decided to integrate the materials provided by that WG with those contributed by the other WGs.

9. Detailed considerations of the research implications of the precautionary approach were carried out at simultaneous meetings of the WGs, these being continuations of their previous

work through e-mail and through informal, opportunistic meetings. Joint meetings between different WGs were held to discuss topics of mutual interest.

10. At the meetings of the WGs, the drafting of parts of the technical document on research implications was finalized. The Convenors of the WGs played a very important role in that. The resulting drafts were submitted to a Plenary Session for its review, comments, and suggestions for improvements. Eventually, after further work within the WGs, the draft document was submitted to a Plenary Session for its adoption.

11. The resulting document, entitled "Research Implications of Adopting the Precautionary Approach to Management of Tuna Fisheries," is likely to be published in a form to be decided by the SC after its editing. Until then, the document will be available at request from the SC at its discretion.

Adjournment

12. On behalf of FAO, Dr Majkowski thanked all contributors to its success, particularly:

- all the tuna fishery bodies and the Secretariat of the Pacific Community (SPC), which co-organized the Consultation and

- the Department of Fisheries of the Royal Government of Thailand, especially the Andaman Sea Fisheries Development Center (AFDEC) and the Phuket Marine Biological Center (PMBC), which assisted with securing local arrangements and for its hospitality for the Consultation, which was also provided by the Thai Oceanic Tuna Fishery Cooperatives, Ltd. (TOTFIC) and the Phuket Fishing Port of the Fish Marketing Organization (FMO) of Thailand.

He also acknowledged:

- the input of the SC to the organization of the Consultation,

- the very efficient chairmanship by Dr Allen, and

- the hard work of the Covenors and the other Members of the WGs.

He extended gratitude also to Dr Veravat Hongskul, Senior Fishery Officer of FAO's Regional Office for Asia and Pacific (RAP) in Bangkok, Thailand, and to the staff of RAP, for making the arrangements for the meeting and for the support and assistance rendered to the Consultation during the meeting.

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TR/M/Y0490E/1/5.01/1600